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## CRYOGENIC FLUID MANAGEMENT EXPERIMENT

by R. N. Eberhardt, W. J. Bailey, and D. A. Fester

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16. Abstract <p>Cryogenic liquid storage and supply systems will play an important role in meeting mission requirements of future NASA and DOD payloads. A first step in the development of spacecraft subcritical cryogenic storage systems is to obtain engineering data on the performance of these systems. The Cryogenic Fluid Management Experiment (CFME) is the first Space Shuttle flight system designed to characterize subcritical liquid hydrogen storage and expulsion in the low-g space environment. The experiment utilizes a fine-mesh screen fluid management device to accomplish gas-free liquid expulsion and a thermodynamic vent system (TVS) to intercept heat leak and control tank pressure.</p> <p>The experiment design evolved from a single flight prototype to provision for a multimission (up to 7) capability. A detailed design of the CFME, a dynamic test article (CFME-TA), and dedicated Ground Support Equipment was generated. All materials and parts were identified, and components were selected and specifications prepared. Long lead titanium pressurant spheres and the flight tape recorder and ground reproduce unit were procured. Experiment integration with the Shuttle Orbiter, Spacelab, and KSC ground operations was coordinated with the appropriate NASA centers, and experiment interfaces were defined. Phase I ground and flight safety reviews were conducted. Procedures were defined and test plans prepared for ground tests, KSC ground and launch operations, and conduction of the flight experiment. Costs were estimated for fabrication and assembly of the CFME, which will become the storage and supply tank for a new Cryogenic Fluid Management Facility (CFMF) to investigate fluid management in space.</p>			
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Martin Marietta Denver Aerospace

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## FOREWORD

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This report was prepared by the Martin Marietta Corporation, Denver Aerospace, under Contract NAS3-21591. The contract was administered by the Lewis Research Center of the National Aeronautics and Space Administration, Cleveland, Ohio. The technical period of performance was from December 1978 to July 1981.

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The data in this report are presented with the International System of Units as the primary units and English Units as secondary units. All calculations and graphs were made in English units and converted to the International Units.



## TABLE OF CONTENTS

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	<u>PAGE</u>
LIST OF FIGURES.....	vi
LIST OF TABLES.....	viii
SUMMARY.....	ix
I. INTRODUCTION.....	I-1
II. DESIGN CRITERIA AND STUDY GUIDELINES.....	II-1
A. Mission Requirements.....	II-1
B. Design Requirements.....	II-3
C. Material Selection.....	II-13
III. EXPERIMENT DESCRIPTION.....	III-1
A. Flight Hardware Experiment Package.....	III-3
1. Liquid Acquisition Device.....	III-7
2. Liquid Hydrogen Tank.....	III-8
3. Vacuum Jacket/Girth Ring/Trunnion Supports.....	III-10
4. Tank Assembly Thermal Control System.....	III-12
5. External Thermal Control System.....	III-16
6. Pressurization System.....	III-17
7. Data Acquisition and Control System.....	III-20
8. Flow Systems.....	III-27
9. Instrumentation/Data Collection.....	III-30
10. Weight Summary.....	III-35
B. Orbiter Interfaces.....	III-37
1. Orbiter Fluid Mechanical Interfaces.....	III-37
2. Orbiter Electrical Interfaces.....	III-40
3. Orbiter/Spacelab Pallet Structural Connections.....	III-40
4. Operation Control Panel.....	III-43
5. Mechanical GSE.Interfaces.....	III-46
6. Electrical GSE.Interfaces.....	III-46
C. Ground Support Equipment Description.....	III-50
1. GSE and Test Tools for Ground Test Program.....	III-50
2. Mechanical Ground Support Equipment/Integration Activity.....	III-56
3. KSC Supplied GSE.....	III-59
4. Electrical Ground Support Equipment.....	III-63
D. CFME-TA Description.....	III-66

## TABLE OF CONTENTS

---

	<u>PAGE</u>
IV. EXPERIMENT OPERATIONS AND SAFETY..	IV-1
A. Ground Operations.....	IV-1
1. Ground Handling and Shipping.....	IV-1
2. Receiving and Inspection.....	IV-1
3. Payload Integration Operations.....	IV-2
4. Pressurant Sphere Servicing... ..	IV-2
5. Orbiter Payload Installation Operations.....	IV-3
6. Vehicle Assembly Building Operations.....	IV-3
7. Launch Pad Activities.....	IV-3
8. CFME Launch Pad Power.....	IV-7
9. Launch Pad Contingency Operations.....	IV-7
10. Post Landing Runway Operations.....	IV-9
11. CFME Removal and Storage.....	IV-10
12. Safety.....	IV-11
B. Flight Operations.....	IV-16
1. Mission Requirements.....	IV-16
2. Orbital Mission Operations.....	IV-18
3. Mission Abort.....	IV-21
4. On-Orbit Abort.....	IV-22
5. CFME Experiment Abort.....	IV-23
6. Safety.....	IV-26
V. EXPERIMENT ANALYSIS.....	V-1
A. Hydrodynamic Analysis.....	V-1
1. Liquid Acquisition Device.....	V-2
2. Outflow Lines.....	V-2
3. Pressurization and Vent Lines.....	V-4
4. Thermodynamic Vent Lines.....	V-5
5. Fill/Drain and Horizontal Drain Lines.....	V-6
B. Thermal Analysis.....	V-7
1. Cryogenic Storage Analysis Model.....	V-7
2. Storage Tank Assembly Thermal Analysis.....	V-12
3. CFME Payload Thermal Analysis.....	V-24
C. Structural Analysis.....	V-30
1. Structural Design Approach.....	V-30
2. Dynamics and Loads Analysis.....	V-30
3. Fatigue Analysis Methodology.....	V-40
4. Stress Analysis.....	V-42

## TABLE OF CONTENTS

---

	<u>PAGE</u>
VI. GROUND TEST PROGRAM.....	VI-1
A. Component Tests.....	VI-3
1. Liquid Hydrogen Tank Burst and Cycle Test.....	VI-3
2. Trunnion Tests.....	VI-5
B. CFME-TA Tests.....	VI-8
1. In-Line Tests.....	VI-8
2. Functional Tests.....	VI-14
3. Environmental Tests.....	VI-19
C. CFME Tests.....	VI-21
1. In-Line Tests.....	VI-21
2. Functional Tests.....	VI-21
3. High and Low Voltage (Off-Design Performance) Tests.....	VI-22
4. Environmental.....	VI-23
VII. CFME PLANNING AND COST ESTIMATE.....	VII-1
A. CFME Program Master Schedule.....	VII-1
B. CFME Program Cost Estimate.....	VII-5
VIII. CONCLUSIONS AND RECOMMENDATIONS.....	VIII-1
A. Conclusions.....	VIII-1
B. Recommendations.....	VIII-1
APPENDIX A ABBREVIATIONS AND ACRONYMS.....	A-1
APPENDIX B CRYOGENIC FLUID MANAGEMENT EXPERIMENT DRAWING TREE...	B-1
REFERENCES.....	R-1
DISTRIBUTION LIST.....	D-1

## LIST OF FIGURES

<u>FIGURE</u>	<u>TITLE</u>	<u>PAGE</u>
I-1	Spacelab Pallet Installation of the Martin Marietta Baseline CFME.....	I-2
I-2	CFME Detail Assembly.....	I-3
II-1	Orbiter Body Axis Coordinate System (from Ref. 1).....	II-9
II-2	Random Vibration Environment for Spacelab Pallet-Mounted Payload.....	II-10
II-3	Orbiter Cargo Bay Acoustic Environment.....	II-11
III-1	CFME LH <sub>2</sub> Storage and Supply Tank Assembly.....	III-1
III-2	CFME LH <sub>2</sub> Tank Assembly.....	III-2
III-3	CFME Tank Penetrations.....	III-4
III-4	CFME Schematic .....	III-5
III-5	Liquid Acquisition Device Configuration.....	III-7
III-6	Liquid Acquisition Device Support Structure.....	III-9
III-7	Trunnion Mounting Configuration.....	III-11
III-8	TVS Heat Exchanger Configuration.....	III-14
III-9	Helium Storage Sphere.....	III-18
III-10	GHe Sphere Mounting Arrangement.....	III-19
III-11	DACS Block Diagram.....	III-21
III-12	Assembled DACS.....	III-24
III-13	DACS and Associated Circuit Boards.....	III-25
III-14	CFME Wiring Diagram.....	III-27
III-15	CFME Tape Recorder.....	III-34
III-16	CFME Orbiter Interfaces.....	III-37
III-17	LH <sub>2</sub> Fill/Drain Valve Panel Interface.....	III-38
III-18	CFME Valve Panel Vent Interfaces.....	III-39
III-19	CFME/Spacelab Pallet Mounting.....	III-42
III-20	Operation Control Panel (OCP).....	III-44
III-21	Helium Servicing Interface.....	III-47
III-22	Tank Vacuum Jacket Pumpout Port.....	III-48
III-23	Flow Line Vacuum Jacket Pumpout Port.....	III-49
III-24	Vertical (Z) Axis Vibration Test Fixture Configuration.....	III-52
III-25	Lateral (Y) Axis Vibration Test Fixture Configuration.....	III-53
III-26	Thermal Vacuum Test Setup.....	III-54
I'I-27	Horizontal Handling Sling.....	III-57
III-28	Vertical Lifting Arm and Sling.....	III-58
III-29	Transportation Skid and Protective Cover.....	III-59
III-30	CFME Flow at KSC.....	III-60
III-31	New CFME T-O Vent Line Configuration.....	III-62
III-32	EGSE Block Diagram.....	III-64
III-33	EGSE Console.....	III-65
III-34	Ground Reproduce Unit.....	III-66
III-35	CFME-TA Schematic.....	III-68
IV-1	CFME Servicing Concept Using the Fuel Cell Servicing System.....	IV-5
IV-2	Representative Hazardous Servicing Timeline.....	IV-6
IV-3	Ground Abort and Malfunction Decision Chart.....	IV-9
IV-4	Typical Seven Day Mission Timeline.....	IV-17
IV-5	On-Orbit Abort and Malfunction Decision Chart.....	IV-27

## LIST OF FIGURES

<u>FIGURE</u>	<u>TITLE</u>	<u>PAGE</u>
V-1	Outflow Line Schematic.....	V-3
V-2	Perssurization and Vent Line Schematic.....	V-4
V-3	Thermodynamic Vent System Schematic.....	V-6
V-4	CSAM Computer Logic Flow Diagram.....	V-8
V-5	Internal Tank Thermodynamics.....	V-10
V-6	Thermodynamic Vent System Model Logic.....	V-11
V-7	CSAM Nodes for Storage Tank Assembly Thermal Analysis.....	V-13
V-8	CFME Schematic Diagram.....	V-14
V-9	Trunnion Support Node Diagram.....	V-17
V-10	Steady-State Trunnion Temperature Distributions and Heat Leaks.....	V-18
V-11	CFME Pressure History and Helium Requirements for Seven Day Baseline Mission.....	V-21
V-12	Mass of Hydrogen Remaining in Storage Tank Throughout Seven Day Baseline Mission.....	V-21
V-13	Revised CFME Pressure History and Helium Requirements.....	V-25
V-14	Revised Hydrogen Storage Mass Throughout Seven Day Mission.....	V-25
V-15	CFME External Environment Analysis Flowchart.....	V-26
V-16	Spacelab Pallet Temperature Versus Time.....	V-27
V-17	CFME External Temperature Profiles (No Shroud/No Power).....	V-27
V-18	Spacelab Pallet Temperature Profile with Thermal Shroud.....	V-28
V-19	CFME External Temperature Profiles (Shroud/No Power).....	V-29
V-20	CFME External Temperature Profiles (Shroud/Power).....	V-29
V-21	Structural Analysis Approach (to PDR).....	V-31
V-22	Structural Analysis Approach (PDR to CDR).....	V-32
V-23	Verification Structural Analysis.....	V-33
V-24	Storage Tank Model.....	V-35
V-25	Vacuum Jacket Model.....	V-36
V-26	CFME Model Details.....	V-36
V-27	CFME Dynamic Model.....	V-37
V-28	CFME First and Second Mode Structural Model.....	V-39
V-29	CFME Storage Tank/Trunnion Idealization.....	V-43
V-30	Trunnion Laminate Composite S/N Curve.....	V-45
VI-1	CFME Ground Test Flow Chart.....	VI-2
VI-2	CFME-TA Schematic.....	VI-9
VI-3	CFME-TA Ground Test Flow Chart.....	VI-10
VI-4	CFME-TA/Ground Test Support Equipment Schematic.....	VI-17
VII-1	CFME Program Master Schedule.....	VII-3

## LIST OF TABLES

<u>TABLE</u>	<u>TITLE</u>	<u>PAGE</u>
II-1	CFME Mission Requirements and Guidelines.....	II-2
II-2	Applicable NASA Documents.....	II-4
II-3	CFME Design Requirements.....	II-5
II-4	Acceleration Environment.....	II-9
II-5	Vibration Environment.....	II-11
II-6	Thermal Environment Inside Cargo Bay.....	II-12
II-7	Material Allowables.....	II-14
III-1	Experiment Data Measurements.....	III-30
III-2	Instrumentation Sensor Description.....	III-31
III-3	Tape Recorder Specifications.....	III-33
III-4	Experiment Weight Summary.....	III-36
III-5	Experiment Power Requirements.....	III-41
III-6	Ground Support Equipment/Test Tooling Matrix.....	III-51
V-1	CFME Hydrodynamic Analysis Summary.....	V-3
V-2	Steady State Heat Inputs to the Liquid Hydrogen Storage Tank.....	V-15
V-3	CFME Quasi-Static Load Design Factors.....	V-34
V-4	CFME Modal Frequencies.....	V-38
V-5	Minimum Margins of Safety.....	V-46
VII-1	Time-phased Budgetary Cost Estimates (Excluding Fee) in 1981 Dollars.....	VII-7

## SUMMARY

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Cryogenic liquid storage and supply systems will play an important role in meeting mission requirements of future NASA and DOD payloads. A first step in the development of spacecraft subcritical cryogenic storage systems is to obtain engineering data on the performance of these systems. The Cryogenic Fluid Management Experiment (CFME) is the first flight system designed to characterize subcritical liquid hydrogen storage and expulsion in the low-g space environment. The experiment utilizes a fine-mesh screen fluid management device to accomplish gas-free liquid expulsion and a thermodynamic vent system (TVS) to intercept heat leak and control tank pressure.

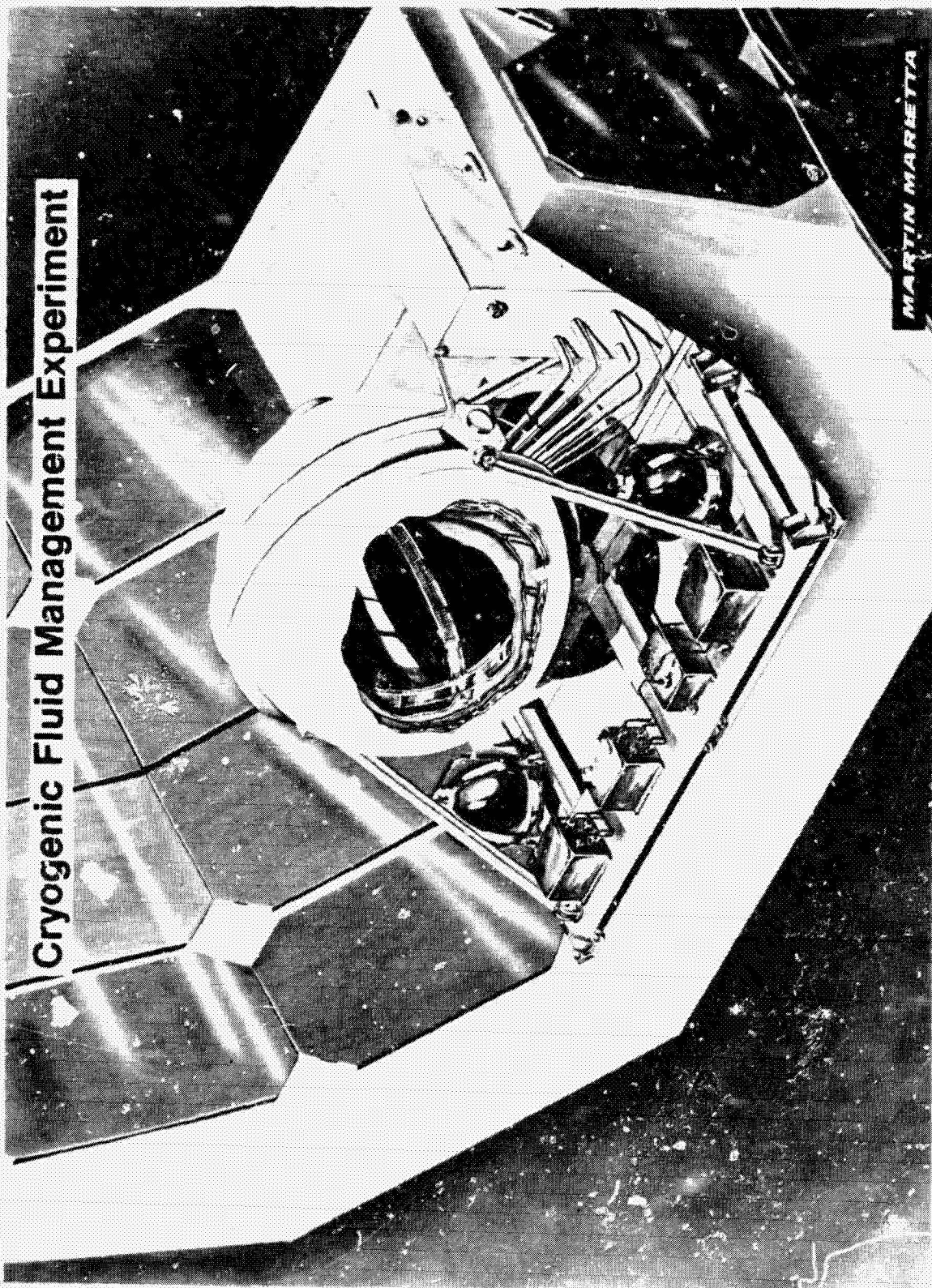
The CFME is designed to be checked out, serviced and launched from the Kennedy Space Center in the cargo bay of the Space Shuttle Orbiter. On orbit, the mission consists of a series of liquid hydrogen expulsions separated by storage periods. Various operating modes are used for the expulsions, altering the thermodynamic state of the delivered liquid in order to collect data over the widest range of conditions. Data collected during storage periods will permit evaluation of the performance of the thermal control system.

The experiment design evolved from a single flight prototype to provision for a multimission (up to 7) capability. This resulted in the addition of a dynamic test article (CFME-TA) to demonstrate the necessary fatigue life. Major structural modifications in the configuration of the tank and support assembly were made as payload design requirements became more definitive. Experiment complexity, payload interface requirements and cost resulted in the desire to make the experiment as automated and autonomous as possible without sacrificing the capability to obtain the desired data from the flight test.

A detailed design of the CFME, CFME-TA, and dedicated Ground Support Equipment was performed together with the required supporting analyses. All materials and parts were identified, and components were selected and component specifications prepared. Instrumentation and experiment control logic were established and a detailed specification was written for the data acquisition and control system. Long lead titanium pressurant spheres and the flight tape recorder and ground reproduce unit were procured.

Experiment integration with the Shuttle Orbiter, Spacelab, and KSC ground operations was coordinated with the appropriate NASA centers, and experiment interfaces were defined. Safety assessments were performed through the Phase I ground and flight safety reviews. Procedures were defined and test plans prepared for ground test of components, subassemblies, and the completed CFME and CFME-TA assemblies, for KSC ground and launch operations, and for conduction of the flight experiment. During the course of the detailed experiment design activity, the overall needs for fluid management in space were reassessed and the project was modified to combine the CFME into a fluid management facility. The CFME will become the storage and supply tank for the new Cryogenic Fluid Management Facility (CFMF). For this phase of the project, however, the CFME remained a discrete and separate system.





**Cryogenic Fluid Management Experiment**

MARTIN MARLETTA

## I. INTRODUCTION

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Cryogenic fluids possess characteristics that make them extremely desirable for future NASA and DOD payload applications which include propellants, power reactants, coolants, and experiment or process consumables. Storing and supplying subcritical, rather than supercritical, cryogens offers advantages in terms of system weight and power requirements but creates problems related to the uncertainty of the liquid-gas interface configuration in a low-g environment. In particular, there is no certain method of venting single-phase gas to relieve excess pressure accumulation due to heat leak without including some liquid management technique.

A first step in the development of spacecraft subcritical cryogenic storage systems is to obtain engineering data regarding liquid storage and supply in space by performing a flight test experiment in a low-g environment. The Cryogenic Fluid Management Experiment (CFME) is the first flight system designed to characterize low-g subcritical cryogenic fluid storage and expulsion, and to measure the performance of these systems. It includes a liquid hydrogen tank containing a fine-mesh screen acquisition device, a thermal control system consisting of thermodynamic vent heat exchangers to intercept heat leak to the liquid hydrogen tank and control tank pressure, and a pressurization system to provide a variety of storage and expulsion operating modes. The CFME liquid hydrogen storage and supply tank and all supporting systems are mounted on a Spacelab pallet, as shown in Figures I-1 and I-2, and carried into orbit within the cargo bay of the Space Shuttle Orbiter.

The objective of the CFME is to obtain data that can be used to establish design criteria for spacecraft subcritical cryogenic storage and supply tankage. The experiment will also serve as a demonstration of the feasibility of combining a fine-mesh screen fluid acquisition system with a thermal control system in a lightweight unit that will provide on-demand, vapor-free liquid cryogens in space. The flight test will be significant in establishing design criteria that can be applied to the design of subcritical tankage up to 4.57 m (15 ft) in diameter. Secondary objectives of the experiment include a pressurization system evaluation, a performance evaluation of trunnion mounts

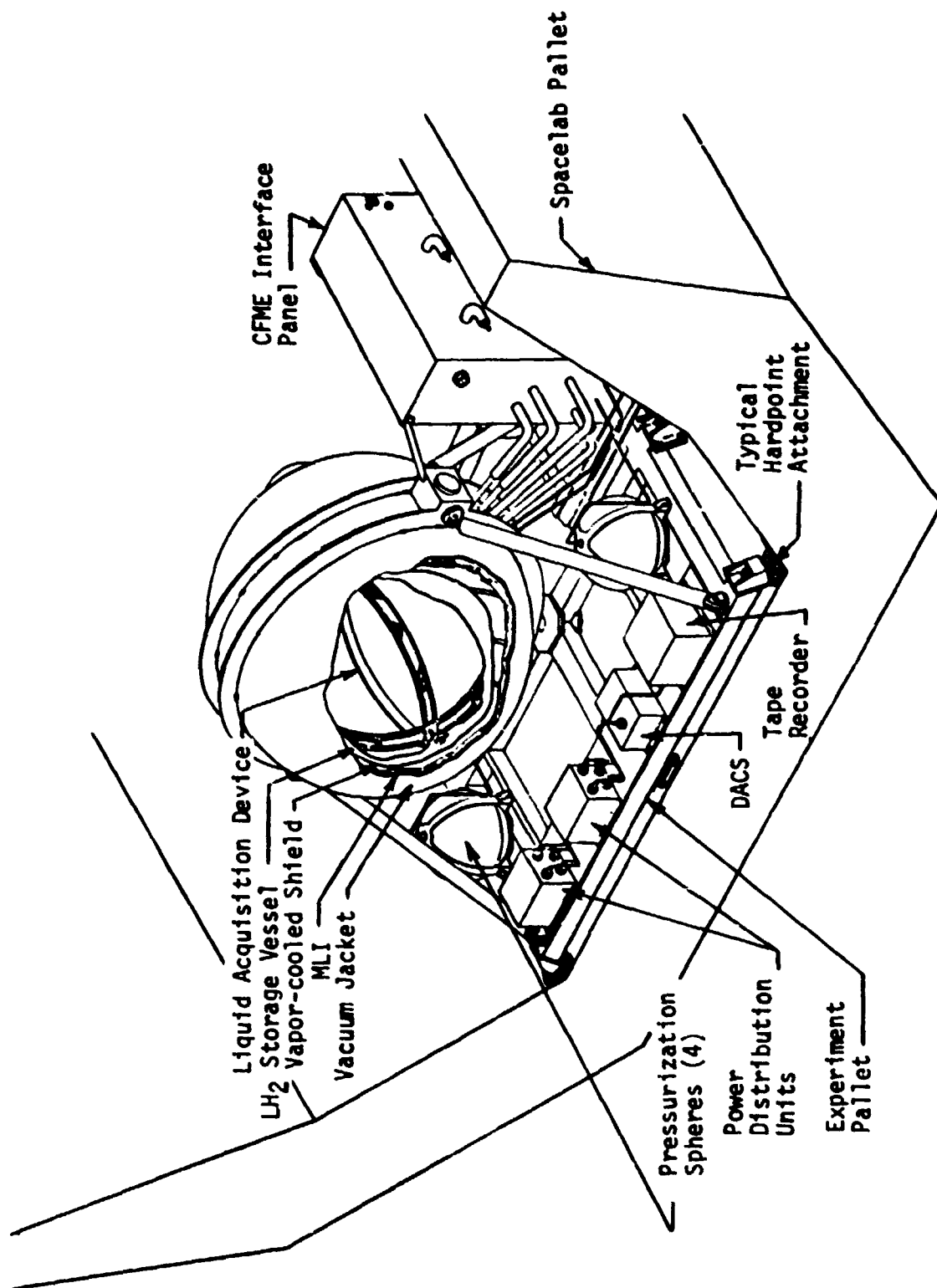


Figure I-1 Spacelab Pallet Installation of the Martin Marietta Baseline CFME

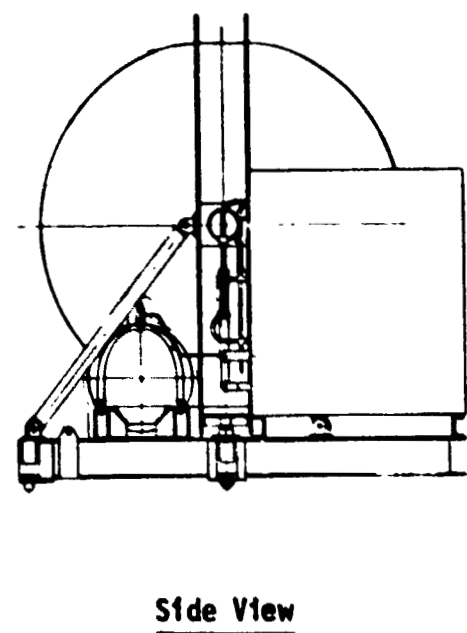
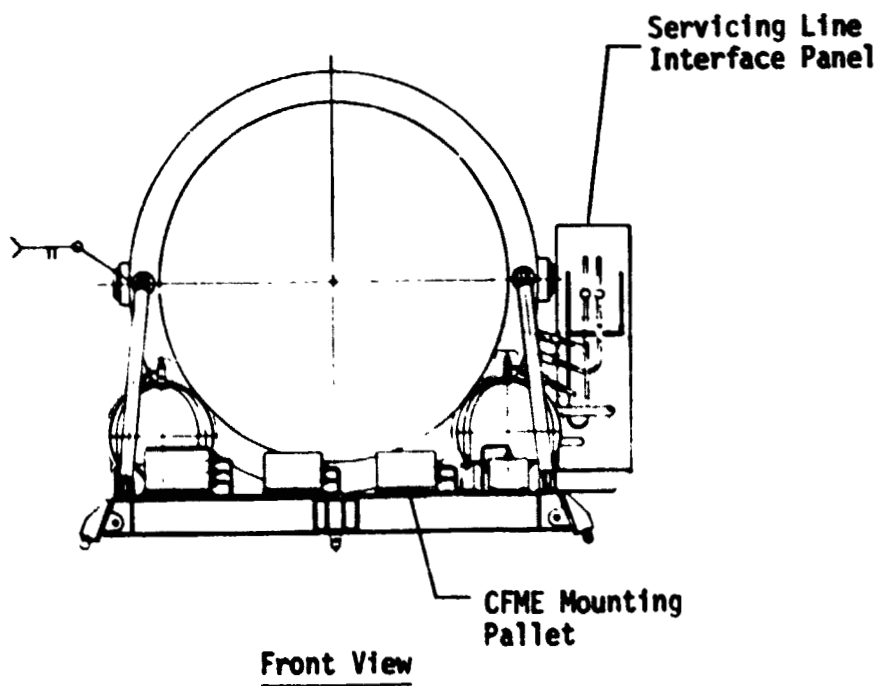
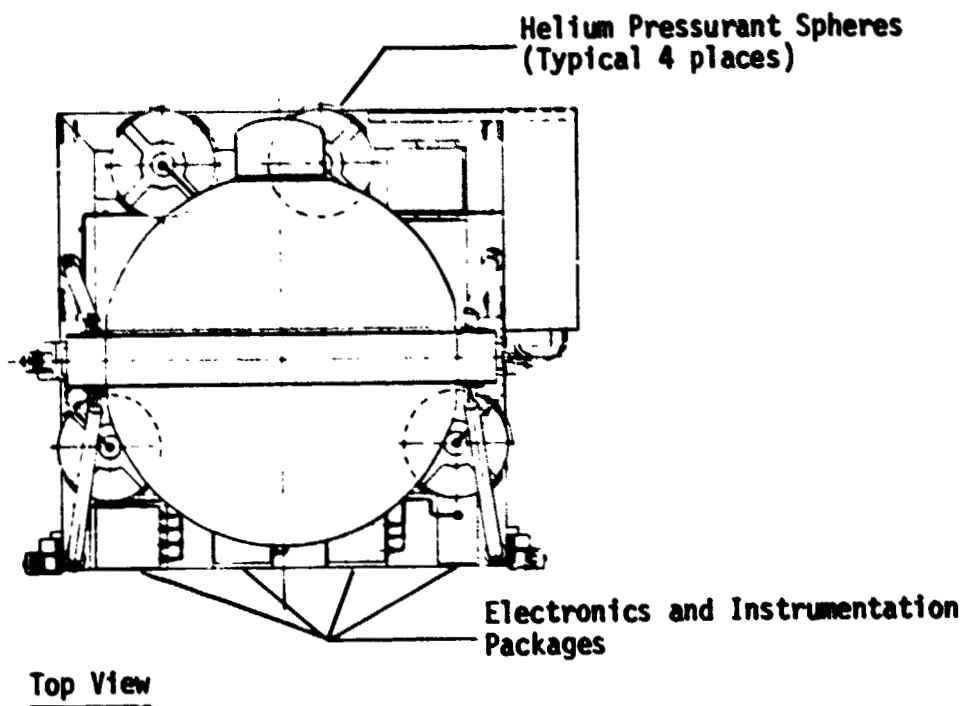


Figure I-2 CFME Detail Assembly

for support of the hydrogen storage vessel within the vacuum jacket, and a vent and outflow fluid mass flow instrumentation evaluation. The program will also permit the validation of analytical models with low-g test data.

The experiment design evolved as payload requirements and integration constraints were established. For example, cost, complexity and payload interface requirements resulted in the desire to make the experiment as autonomous as possible, without sacrificing the capability to obtain the desired data from the flight test. As the payload design requirements became more definitive, major structural modifications were needed in the configuration of the tank assembly. Cost was a major consideration in component definition and selection.

Experiment design was primarily dictated by the experiment objectives. However, many other constraints were also imposed by the experiment support structure and test support facilities, and by the implementation procedures. This translated into design impacts resulting from Spacelab pallet and Shuttle Orbiter capabilities and provisions, ground facility provisions, integration restrictions, and ground and flight operational procedures and safety considerations. Since liquid hydrogen was the test fluid all aspects of the CFME design and operation were thoroughly documented and reviewed.

A variety of tasks and activities were performed in producing the CFME detail design. These were:

- o Definition of the experiment hardware and its operation in space.
- o Preparation of detailed engineering drawings of the CFME, CFME dynamic test article (CFME-TA) and dedicated ground support equipment (GSE), and schematic drawings of the ground test fixtures.
- o Preparation of parts and materials lists, and material processes and fabrication specifications.
- o Conduct of supporting hydrodynamic, material, structural and thermal analyses.

- o Selection of all experiment components and the writing of detailed specifications for planned procurement. Procurement of long-lead items including pressurant spheres and the flight tape recorder and its ground reproduce unit.
- o Definition of experiment instrumentation and control equipment, including preparation of a detailed specification for the data acquisition and control system (DACS).
- o Definition of experiment flight interfaces with the Shuttle Orbiter and Space Lab, and ground interfaces during experiment ground processing and launch pad operations. Experiment integration was a significant part of this activity.
- o Conduct of safety analyses and design for "fail-safe" operation with total containment (no release of hydrogen within the cargo bay). This included preparation of the Phase 0 and Phase I Safety Compliance Data Packages and support of the ground and flight safety reviews for both phases.
- o Conduct of a Preliminary Design Review and a Critical Design Review covering all aspects of the program.
- o Definition of procedures and preparation of test plans for ground test of components, subassemblies, and the completed CFME and CFME-TA assemblies; plans for KSC ground and launch operations including abort; and the flight experiment orbital operations plan including inserting and abort.
- o Preparation of cost estimates for CFME, CFME-TA and GSE fabrication, assembly and testing.
- o Travel in support of the various reviews and interface meetings.
- o Conduct of product assurance during all aspects of the program.
- o Program reporting.

Mission requirements and study guidelines for the CFME design are presented in Chapter II, and the resulting experiment description is contained in Chapter III. The CFME flight hardware, the CFME-TA ground test article, the Orbiter interfaces and the associated ground support equipment are each described. Experiment ground and flight operations, and safety aspects of each, are summarized in Chapter IV. Chapter V summarizes the hydrodynamic, thermal and structural analyses and Chapter VI summarizes the component, CFME-TA and CFME ground test programs. CFME planning and cost estimates for fabrication, assembly and ground testing are presented in Chapter VII.

## II. DESIGN CRITERIA AND STUDY GUIDELINES

---

Various criteria and guidelines were used in arriving at the final design of the CFME. These included mission requirements, general experiment configuration and approach, mounting on a Spacelab pallet with the accompanying Shuttle cargo bay environment, and maximum utilization of existing ground support systems at the Kennedy Space Center (KSC).

### A. Mission Requirements.

A summary of CFME mission requirements is presented in Table II-1. The configuration and interfaces of both the CFME and ground support equipment (GSE) are impacted by these requirements. In some cases, such as no special mission low-g acceleration requirements, maximum flexibility is possible for mission assignment. In other cases, such as a non-solar-facing mission, the requirement imposes a limitation.

Pallet sill hardpoints were not used for mounting to allow for the possibility of another experiment mounted over the CFME. The experiment requires power prior to Spacelab power-up and this must be obtained from the Orbiter essential bus. The crew will be occupied with preparation to terminate the mission and return to Earth during the last 16 hours, and the experiment operation must be completed prior to this time.

The need for a caution and warning interface was not established ; rather, a CFME Operation Control Panel (OCP) on the Aft Flight Deck was defined. Indicators on the OCP provide the flight crew with a status of how the experiment is working. Since the experiment is automated, and all contingencies are handled automatically, safe operation is provided without crew involvement. The use of the OCP for status and control was discussed at the Phase I Flight Safety review and approved as a satisfactory approach to safety as contrasted to the alternative of a dedicated caution and warning system. The safety committee approach to caution and warning systems has been to minimize as far as possible the dependence on this approach so the crew can concentrate on the STS-related operations rather than having to initiate and



*Table II-1 CFME Mission Requirements and Guidelines*

INTEGRATION

- No special mission low-g acceleration requirements.
- Non-solar-facing mission
- Pallet sill hard points not available for experiment mounting
- Use power from Orbiter essential bus prior to Spacelab power-up.
- Seven (7) day mission (last 16 hours unavailable).
- No caution and warning interface.
- CFME Operation Control Panel on Aft Flight Deck.

GROUND OPERATIONS

- Loading of He pressurant spheres in Operations and Control (O and C) building.
- Fuel Cell Servicing System (FCSS) available for LH<sub>2</sub> loading.
- Load CFME before Orbiter Power Reactant Storage Assembly (PRSA) tanks.
- Use Orbiter power for ground operations.
- Tape recorder data dump using NASA facilities.

ABORT OPERATIONS

- Power Reactant Storage and Distribution (PRSD) GSE available for runway detanking
- PRSD GSE in Orbiter Processing Facility (OPF) available for contingency detanking
- 28 VDC power from portable GSE at the landing site will be used for CFME power during a Return-to-Launch-Site (RTL) abort (Orbiter fuel cell power may be secured immediately after landing).

monitor corrective action for a payload. The selected ground operation approaches are those preferred by the ground processing and servicing personnel at NASA-KSC. This is also true of the provisions for abort operations.

#### B. Design Requirements.

All design, fabrication, test, safety, and interfacing/integration activities with regard to CFME, CFME-TA, and GSE were performed in compliance to the documents listed in Table II-2. It is recognized that more recent issues/revisions exist; however, those listed in Table II-2 were the formal contract documents at the time of design completion.

A summary of the performance requirements together with the structural requirements from References 1 through 3 are presented in Table II-3. The specific elements of the CFME addressed in the table are the liquid acquisition device, hydrogen storage vessel, thermal control system, vacuum jacket, support structure, pressurization and vent system, electronics and ground support equipment.

Environmental conditions applicable to the design of the CFME were compiled from References 1 and 2. The accelerations occurring during lift-off and landing are listed in Table II-4 per the axes definition presented in Figure II-1. The sine and random vibration environments for the experiment are listed in Table II-5. The random vibration spectrum is shown in Figure II-2. Events such as wind gusts, engine ignition and cutoff, separation, and docking will induce the low-frequency sine vibration environment. Random vibration is produced during launch from the overall acoustic level inside the cargo bay, and is specifically defined for pallet-mounted experiments. The acoustic noise spectrum given by Figure II-3 is the maximum predicted level for pallet-mounted experiments during launch. The entry spectrum is significantly less.

The pallet structure surface temperature extremes for hot and cold case conditions with the cargo bay doors open are presented in Table II-6. These extremes are maximums per SPAH SLP/2104. The actual temperature extremes that

Table II-2 Applicable NASA Documents

NHB 1700.7 May 1979	NASA Headquarters. Office of Space Flight, Safety Policy and Requirements for Payloads using the Space Transportation System.
JSC 11123 Change 1 Sept. 1978	Space Transportation System Payload Safety Guidelines Handbook.
K-STSM-14.1 March 14, 1978	KSC Launch Site Accommodations Handbook for STS Payloads
JSC 13830 May 1979	Implementation Guide for "Safety Policy and Requirements for Payloads using the Space Transportation System."
JSC 07700 Vol XIV Change 30 10-05-79	Space Shuttle Payload Accommodations, Level II. Program Definition and Requirements.
SLP 2104 Issue 1 Rev. 2 July 31, 1979	<p>Spacelab Payload Accommodation Handbook. The following groundrules shall apply in the use of the SPAH SLP/2104:</p> <ol style="list-style-type: none"> <li>1) Assume that power will be available during all portions of the mission, including ascent.</li> <li>2) Use Appendix A, Issue 1, 31 July 1978, "Avionics Interface Definition."</li> <li>3) Use Appendix B-1, Issue 1, 28 February 1979, "Structure Interface Definition. Pallet."</li> <li>4) Appendix B, Issue 1, Revision 1, 31 May 1979, "Structure Interface Definition. Module" is not applicable.</li> <li>5) Appendix C, "Thermal Interface Definition", is not applicable.</li> <li>6) Appendix D, "Software Interface Definition", is not applicable.</li> </ol>
JSC SL-E-0002 Rev. A Sept. 16, 1974	Electromagnetic Interference Characteristics Requirements for Equipment.

Table II-3 CFME Design Requirements

LIQUID ACQUISITION DEVICE

- Expel gas-free LH<sub>2</sub> in the low-g, on-orbit environment at a maximum flowrate of 81.6 kg/hr (180 lbm/hr).
- Provide a minimum flowrate of 1.5 kg/hr (3.3 lbm/hr).
- Expel to a residual of 2 percent or less.
- Perform an abort dump of a full tank while in a low-g environment, within 30 minutes, at a flowrate of 81.6 kg/hr (180 lbm/hr).
- Limit load shall be 1.0 times the load derived from a dynamic analysis based on the environments defined in SPAH SLP/2104.
- Ultimate load shall be at least 1.5 times limit load.
- Design for seven-mission life.

HYDROGEN STORAGE VESSEL

- Limit pressure shall be 2.5 times operating pressure.
- Ultimate pressure shall be at least 1.5 times limit pressure.
- Design collapse pressure shall be 103 kN/m<sup>2</sup> (15 psi) at 200C (680F). (This corresponds to a 1.25 factor on the in-line test condition).
- Limit load shall be 1.0 times the load derived from a dynamic analysis based on the environments defined in SPAH SLP/2104.
- Ultimate load shall be at least 1.5 times limit load.
- Combined loading conditions shall consider limit pressure-limit load, and ultimate pressure-ultimate load as defined above.
- No structural element shall yield or experience excessive deformation at limit load.
- No structural element shall fail by stress, instability rupture, or other material cause at ultimate load.
- Maximum operating pressure shall be assumed to occur at ambient temperature, 200C (680F), which is the worst-case design condition. (Material allowables are greater at cryo temperatures).
- Vessel shall be proof pressure tested at 2.0 times operating pressure.
- The vessel shall have penetrations and lines to permit abort draining in either vertical or horizontal attitudes.

Table II-3 CFE Design Requirements (cont)

HYDROGEN STORAGE VESSEL (Continued)

- Materials with no significant hydrogen embrittlement shall be used.
- Shall meet requirements of MIL-STD-1522.
- Design for seven-mission life.

THERMAL CONTROL SYSTEM

- 7-Day LH<sub>2</sub> storage.
- Thermodynamic vent system with capability to control tank pressure to  $\pm 0.7 \text{ kN/m}^2$  ( $\pm 1 \text{ psi}$ ).
- Ground hold capability up to 28 hr from loading without exceeding control pressure of  $379 \text{ kN/m}^2$  (55 psia).
- Optimize to minimize weighted sum of two times vented hydrogen weight and the weight of MLI for a 7-day storage period.
- Prevent boiling of liquid at tank outlet.
- Vent only vapor from the thermodynamic vent system (at exit from VCS).
- Design for seven-mission life.

VACUUM JACKET

- Design collapse pressure shall be  $155 \text{ kN/m}^2$  (22.5 psi) at the maximum shell temperature of 73°C (163°F). (This corresponds to a 1.5 factor on sea level atmospheric pressure.)
- Limit load shall be 1.0 times the load derived from a dynamic analysis based on the environments defined in SPAH SLP/2104.
- Ultimate load shall be at least 1.5 times limit load.
- Combined loading conditions shall consider  $103 \text{ kN/m}^2$  (15 psi) collapse pressure-limit load, and design collapse pressure-ultimate load as defined above.
- No structural element shall yield or experience excessive deformation under combined limit loads.
- No structural element shall fail by stress, instability rupture, or other material cause at ultimate load.
- Design for seven-mission life.

Table II-3 CFME Design Requirements (cont)

#### SUPPORT STRUCTURE

- Structure shall be designed for seven-mission life.
- Limit load shall be 1.0 times the load derived from a dynamic analysis based on the environments defined in SPAH SLP/2104.
- Ultimate load shall be at least 1.5 times limit load.
- No structural element shall yield or experience excessive deformation at limit load.
- No structural element shall fail by stress, instability rupture, or other material cause at ultimate load.
- The structure shall interface with standard Spacelab payload points.
- The fundamental mode of the experiment mounted on the support structure shall have a frequency of at least 35 Hz.
- The structure shall be self-supportive.

#### PRESSURIZATION AND VENT SYSTEM

- Provide gaseous helium to the hydrogen storage vessel during subcooled outflow of liquid hydrogen.
- While operating, maintain LH<sub>2</sub> tank pressure within  $\pm 0.7 \text{ kN/m}^2$  ( $\pm 1 \text{ psi}$ ) of operating pressure.
- Supply sufficient pressurant to maintain abort dump rate of 81.6 kg/hr (180 lbm/hr) in both vertical and horizontal tank orientations.
- Provide adequate gaseous helium to purge and inert experiment before or after landing.
- Provide sufficient vent flow area to accommodate excess boil-off during tank loading and in the event of thermal control system failure.
- Helium storage vessel shall meet requirements of NSS/HP-1740.1.
- Helium storage vessel temperature shall not exceed 60°C (140°F).
- Design for seven-mission life.

*Table II-3 CFME Design Requirements (cont.)*

ELECTRONICS

- Provide automatic data collection and operational control through microprocessor.
- Minimize the Mission Specialist involvement in experiment operations.
- Tape record experiment data during launch countdown, ascent, and on-orbit operation.
- Provide Mission Specialist control of experiment for on/off, outflow and abort modes.
- Provide programmed outflow, inerting and abort sequences.
- Design for seven-mission life.

GSE

- Provide capability for lifting and handling the CFME.
- Provide protection of the CFME to prevent damage during handling.
- Provide control and monitoring of the pressurization and hydrogen load/offload operations.
- Provide capability for helium pressurization of the CFME.
- Provide capability to load and offload the CFME with hydrogen, and inert the CFME.
- Provide experiment interface panel for connection to the existing helium and hydrogen facilities at KSC, to the Shuttle Orbiter midbody and T-0 umbilical panels, and to Orbiter power and Aft Flight Deck cable connections.

Table II-4 Acceleration Environment

<u>Pallet-Mounted Payload Accelerations</u>						
	Acceleration, g			Acceleration, rad/sec <sup>2</sup>		
	X	Y	Z			
Lift-off	+2.11	+1.4	+5.5 -6.1	+1.9	+5.8	+0.7
Landing	+4.0	+1.0	+6.6 -4.0	+3.4	+6.0	+1.2

<u>On-Orbi. Accelerations</u>	
Orbital Maneuvering System (OMS)	0.077 g in +X Direction
Reaction Control System (RCS)	0.04 g Omnidirectional
Coast Drag (185.2 km-100 nmi orbit)	$2.5 \times 10^{-5}$ g
Maximum Coast Acceleration	$1 \times 10^{-4}$ g

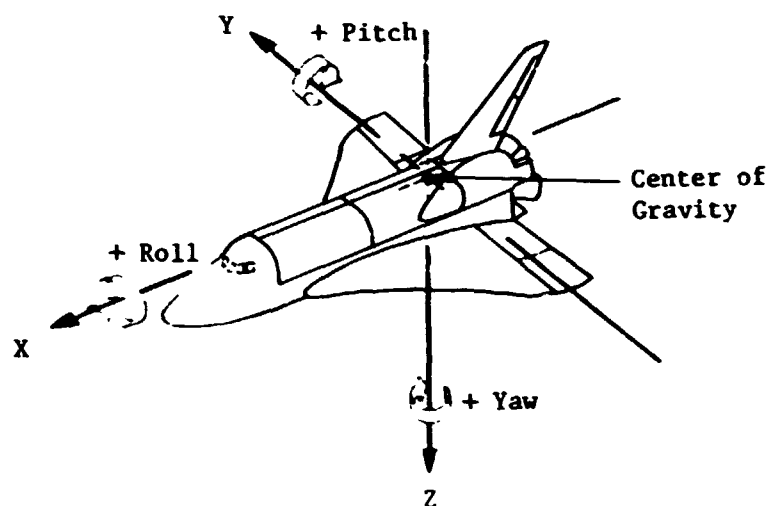


Figure II-1 Orbiter B Axis Coordinate System (from Ref. 1)



(SLP/2104 - Spacelab Payload Accommodations Handbook)

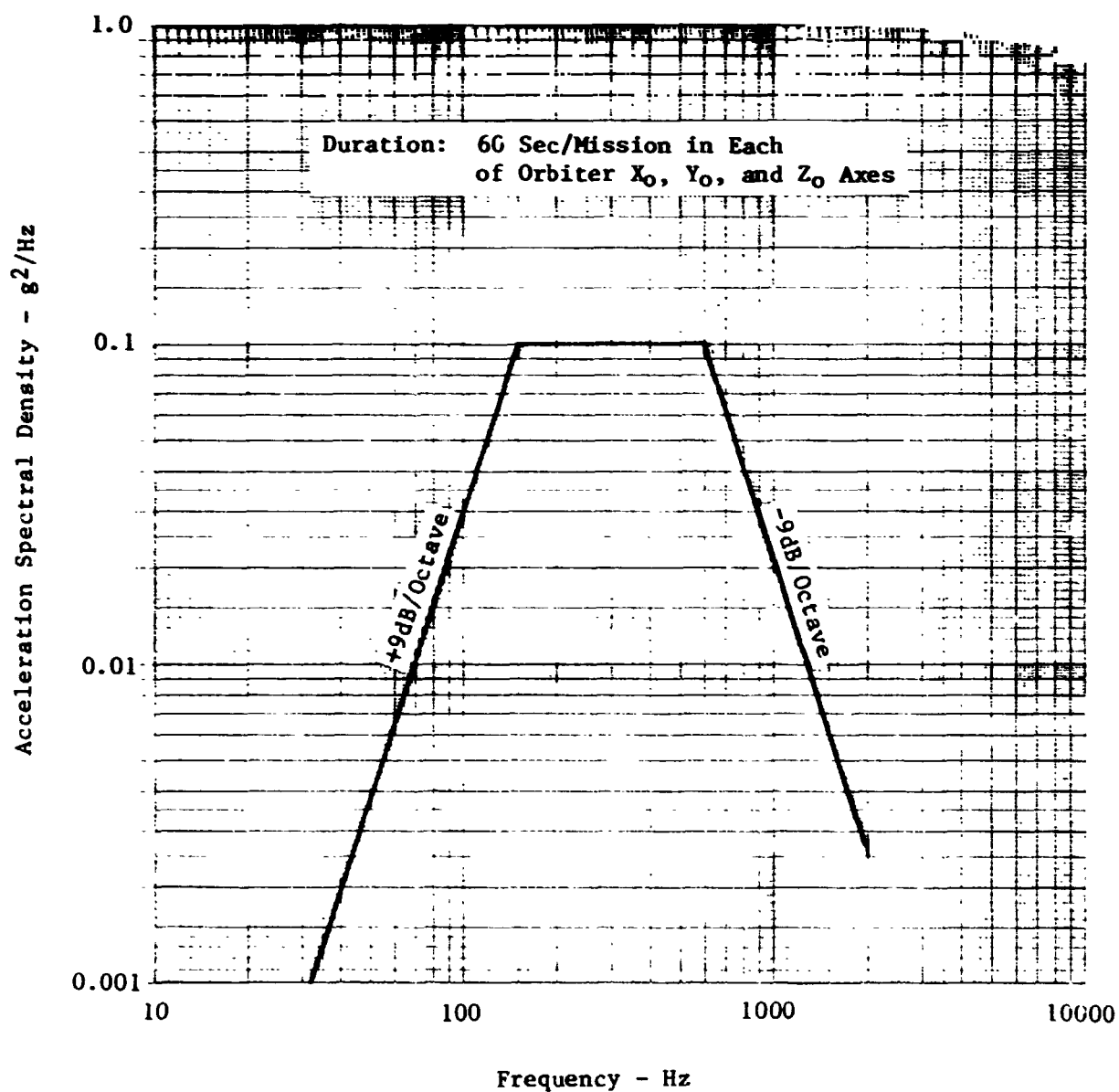


Figure II-2 Random Vibration Environment for Spacelab  
Pallet-Mounted Payload

Table II-5 Vibration Environment

<u>Sine Vibration</u> - Assembled Payload Level	
Frequency Range:	5 to 35 Hz
Level:	$\pm 0.25$ g (Zero to Peak)
Sweep Rate:	1 Octave/min (1 Sweep Up and Down)
Axes:	3 Principal Axes

<u>Random Vibration</u> - Payload Mounted to Pallet Hard Points	
<u>Frequency</u>	<u>Level</u>
20 Hz	0.00024 g <sup>2</sup> /Hz
20 to 150 Hz	+9 dB/Octave
150 to 600 Hz	0.10 g <sup>2</sup> /Hz
600 to 2000 Hz	-9 dB/Octave
2000 Hz	0.0027 g <sup>2</sup> /Hz
Composite Level:	8.72 g rms
Axes:	3 Principal Axes
Duration:	60 sec in each of 3 Principal Axes

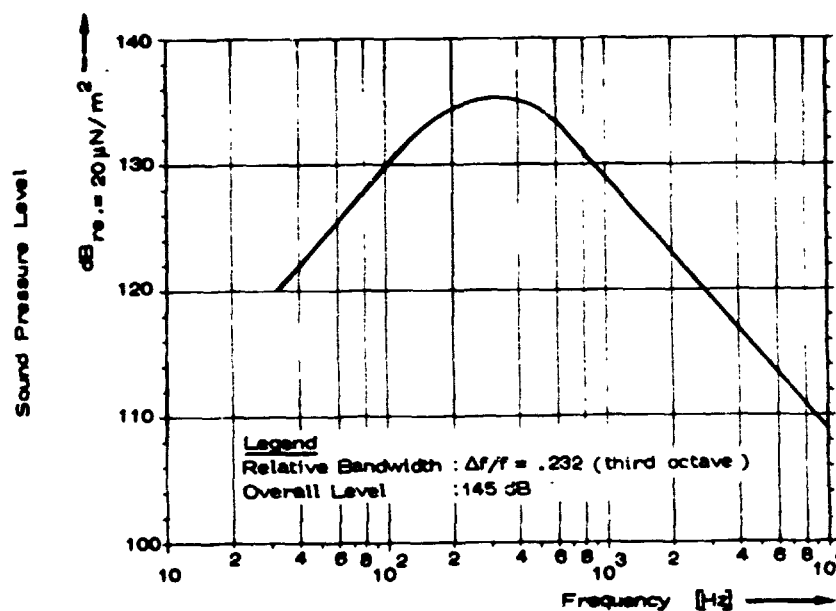


Figure II-3 Orbiter Cargo Bay Acoustic Environment

Table II-6 Thermal Environment Inside Cargo Bay

Worst Case Hot Environment

- o All surfaces inside the cargo bay which can be viewed by the tank assembly are at 3930K (7080R), and are effectively black.
- o Cargo doors are open and the sun is viewed directly overhead with solar radiation flux of 1400 W/m<sup>2</sup> (444 Btu/hr-ft<sup>2</sup>). At the same time, deep space is viewed with a sink temperature of absolute zero.

Worst Case Cold Environment

- o All surfaces inside the cargo bay which can be viewed by the tank assembly are at 1230K (2220R), and are effectively black.
- o Cargo bay doors are open and deep space is viewed with a sink temperature of absolute zero.

Worst Case Transient, Cold to Hot

- o All surfaces inside the cargo bay which can be viewed by the tank assembly or to which the assembly is mounted, go from 1230K (2220R) to 3930K (7080R) following an exponential curve such that 95 percent of the change occurs in 23 minutes. The remaining 5 percent of the change is linear, reaching maximum temperature in 30 minutes.

Worst Case Transient, Hot to Cold

- o All surfaces go from 7080R to 2220R following an exponential curve such that 95 percent of the change occurs in approximately 68 minutes. The remaining 5 percent of the change is linear, reaching minimum temperature in 90 minutes.

Maximum Time at Extreme Conditions

- o Maximum time that extreme conditions will exist is 2 hours. The environmental temperature will then cycle toward the other condition. This gives the maximum cycle time:

Hot condition	2.0 Hours
Hot to cold	1.5 Hours
Cold conditions	2.0 Hours
Cold to hot	<u>0.5 Hours</u>
Total maximum cycle time	6.0 Hours

the CFME will see are dependent on the particular mission on which it is flown, and the content, location and packaging of other experiments in relation to the CFME. A temperature profile of the cargo bay and CFME components and packages will be provided by the Spacelab mission manager once a mission assignment is made. Since the temperature profile was not known, a particular temperature profile was baselined with the aid of NASA-LeRC for the purposes of CFME design. This profile is included in Table II-6.

Safety requirements for Shuttle payloads are specified in References 4 and 5 while Reference 6 presents suggested design and operational options for the elimination and/or control of hazards.

#### C. Material Selection.

The primary materials selected for the CFME storage and supply tank are summarized in Table II-7. These are aluminum for tankage materials, stainless steel for the liquid acquisition device and S-glass/E-glass composite for structural supports.

Tensile strength and good weldability are of prime importance to a vessel designed for burst and 6061-T6 aluminum was selected over 2014-T6 and 2219-T62 due to the better weldability of the 6061-T6. Stainless steel was chosen for the channels and other elements of the liquid acquisition device because of its high strength and stiffness as well as its compatibility/weldability with the screen being used. The 325x2300-mesh, Dutch-twill woven wire cloth, constructed of 304L stainless steel, is preferred for fine-mesh screen acquisition devices because of its high capillary retention capability (high bubble point) and its excellent fabricability characteristics.

Composites are attractive as structural attachment members because of their low thermal conductivity and because they have relatively high strength. The main problem with using these materials is the relatively small amount of data available on allowables at cryogenic temperatures. Also, practically no information is available on fatigue life expectancy, especially at cryogenic temperature. These problems, or shortcomings, are further amplified by the uncertainties resulting from incorporation of the basic materials into a composite lay-up. Further evaluation and classification of

Table II-7 Material Allowables

Material	Room Temperature Properties* 21°C (70°F)	Cryogenic Properties**, -253°C (-423°F)
6061-T6 Aluminum  FT <sub>U</sub> FT <sub>Y</sub> E	290 MPa (42 ksi) 248 MPa (36 ksi) 68 GPa (9.9x10 <sup>3</sup> ksi)	455 MPa (66 ksi) 310 MPa (45 ksi) 76 GPa (11x10 <sup>3</sup> ksi)
Annealed 321 Stainless Steel  FT <sub>U</sub> FT <sub>Y</sub> E	517 MPa (75 ksi) 207 MPa (30 ksi) 200 GPa (29x10 <sup>3</sup> ksi)	1345 MPa (195 ksi) 276 MPa (40 ksi) 210 GPa (30.5x10 <sup>3</sup> ksi)
S-Glass/E-Glass *** Cloth Composite  FT <sub>U</sub> E	334 MPa (48.5 ksi) 42 GPa (6.2x10 <sup>3</sup> ksi)	

\* From MIL-HBK-5C (for metals)

\*\* From Cryo. Mat. Data Hbk., Air Force Materials Lab. (for metals)

\*\*\*Composite Layup properties using SQ5 program (Ref. 30)

lay-up techniques to arrive at required properties, design specifications and manufacturing processes for the composites are required. A test plan for verifying trunnion design data was prepared and a summary of that plan is presented in Chapter VI.

### III. EXPERIMENT DESCRIPTION

The baseline CFME design is presented in this Chapter. The major elements of the experiment which meet the design and mission requirements tabulated in Chapter II are identified. A drawing tree of the CFME detailed design is included in Appendix B for reference purposes.

A schematic of the hydrogen storage and supply tank assembly is shown in Figure III-1. A more detailed layout drawing of the tank assembly is shown in Figure III-2. Two trunnion supports position and hold the storage vessel within the vacuum jacket. One trunnion support is fixed while the other is allowed to float in order to alleviate thermal expansion and contraction loads. An anti-torsion bracket supports the valve assembly at the storage vessel outlet and provides torsional rigidity to the trunnion assemblies for meeting the 35 Hz fundamental mode requirement.

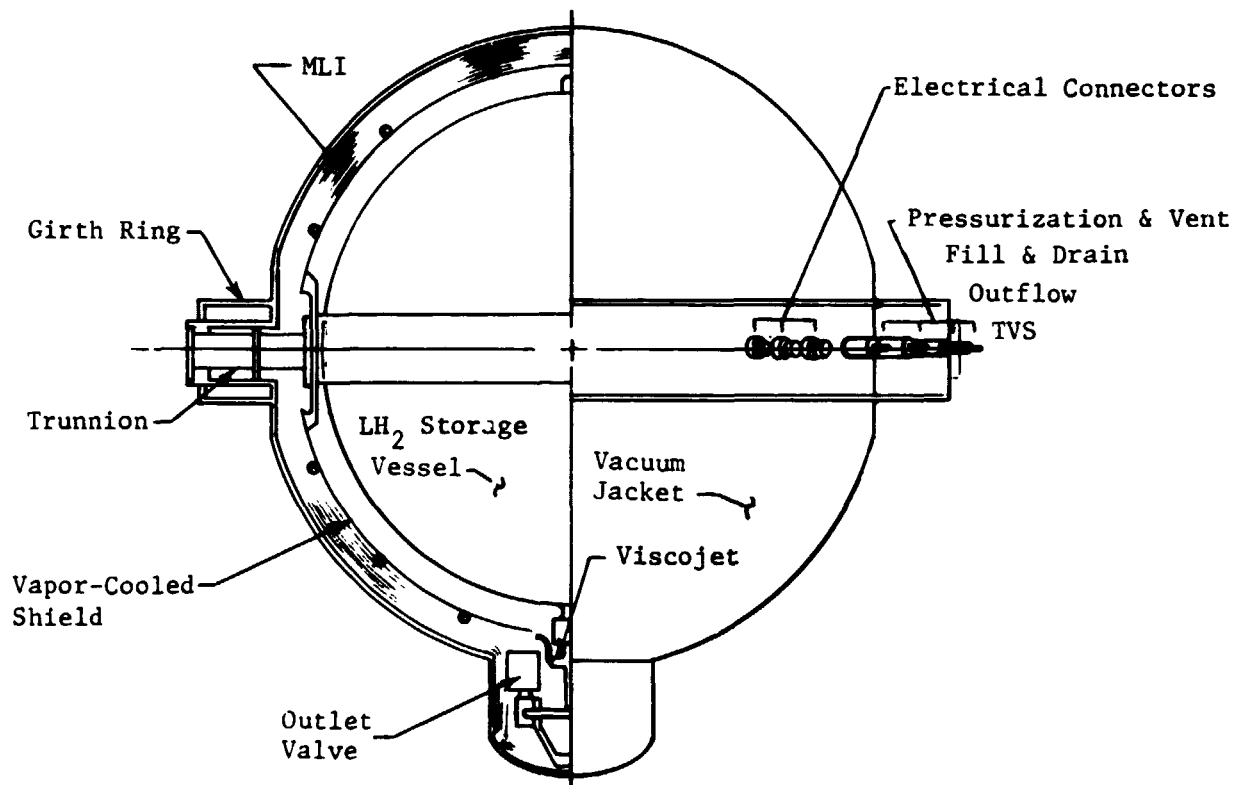
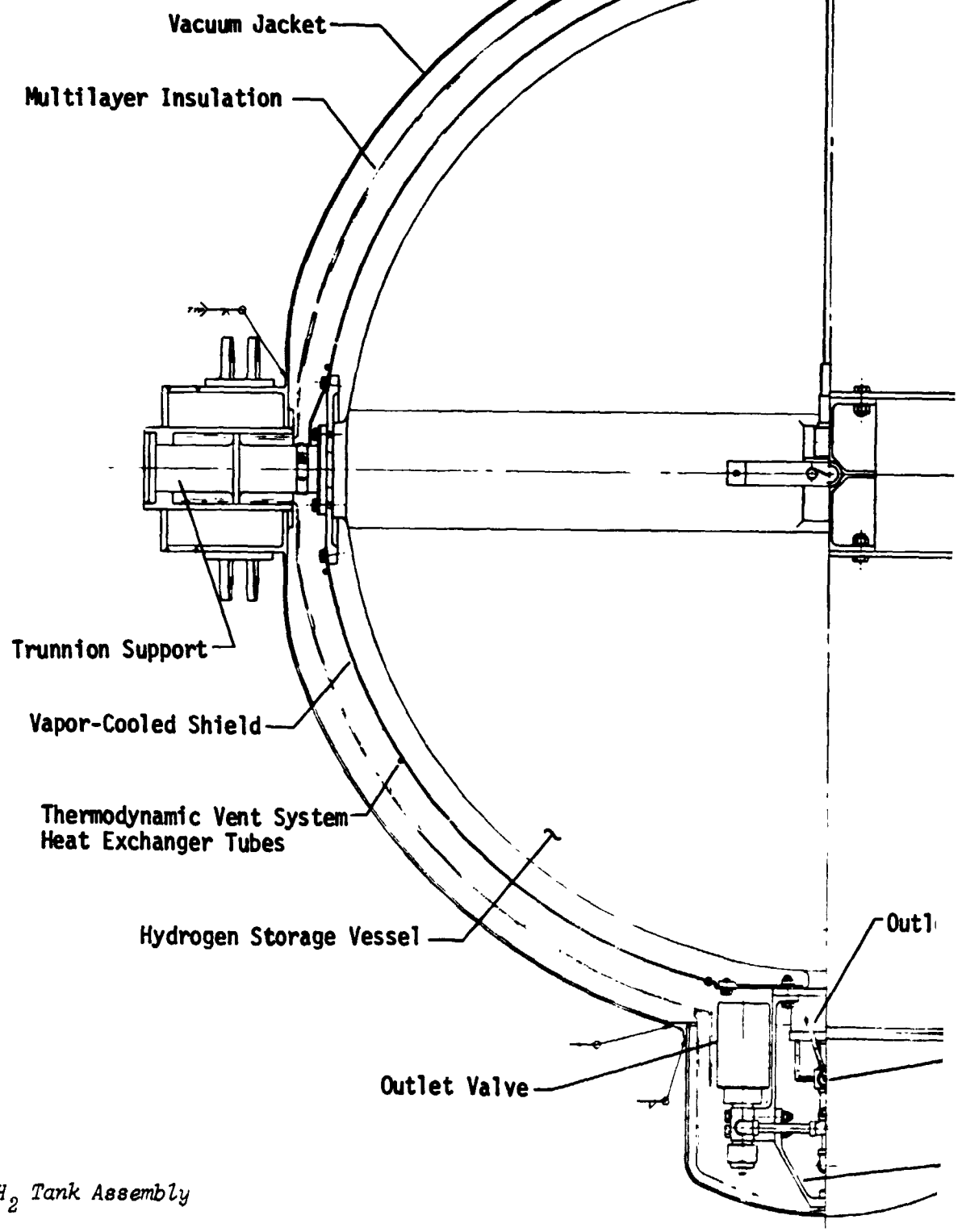


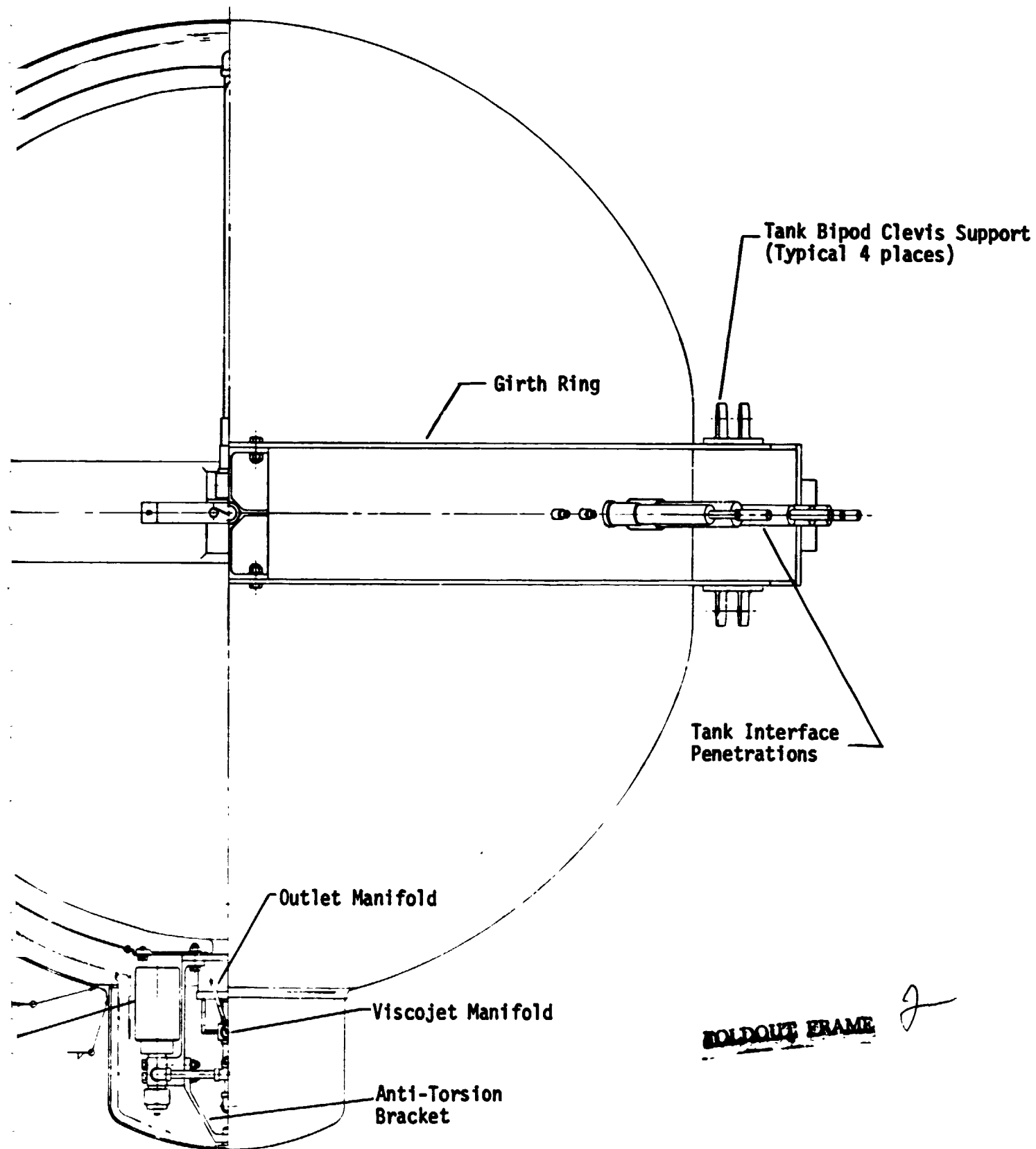
Figure III-1 CFME LH<sub>2</sub> Storage and Supply Tank Assembly

**BOLDOUT FRAME**

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*Figure III-2 CFME LH<sub>2</sub> Tank Assembly*



**BOLDOUT FRAME**

2



Two thermodynamic vent heat exchanger lines, a liquid hydrogen outflow line, a fill/drain line, a pressurization/vent line, a horizontal drain line and a horizontal vent line interface with the tank assembly. The tank assembly penetration of these lines is through the vacuum jacket girth ring as shown in Figure III-3. The pressurization/vent, fill/drain and outlet lines are vacuum-jacketed external to the tank assembly. It may be possible depending upon line length to foam insulate the pressurization/vent line. The horizontal drain and horizontal vent lines will require at least foam insulation to prevent the formation of liquid air within the payload bay. These lines are routed to an experiment-contained interface panel. From there, the lines are routed to the Shuttle external interfaces.

#### A. Flight Hardware Experiment Package.

The CFME flight hardware package consists of the systems necessary to store and expel liquid hydrogen in a low-g environment and to measure the performance of these systems. A schematic, showing the interrelationship of the experiment elements, is presented in Figure III-4. The CFME is a modular experiment with the various elements mounted on an experiment pallet, which is itself mounted on a Spacelab pallet at the pallet hardpoints. The flight hardware is composed of the following systems:

- o Liquid Acquisition Device (LAD). A surface tension device using fine-mesh screen is used to expel gas-free LH<sub>2</sub> from the storage vessel in the low-g environment.
- o Liquid Hydrogen Tank. A 106-cm (41.7-in) diameter aluminum vessel holds a quantity of 600 liters (160 gal) of LH<sub>2</sub> at a maximum operating pressure of 413 kN/m<sup>2</sup> (60 psia). Hot wire point level sensors are mounted within the tank and used during liquid loading to indicate when the desired fill level has been obtained.
- o Vacuum Jacket (VJ). An aluminum vacuum jacket surrounds the liquid hydrogen tank, permitting the annular space to be evacuated. The vacuum jacket is essential to the tank thermal control during launch operations and ascent. It also provides mounting points for the tankage and protection of the multilayer insulation (MLI). A small

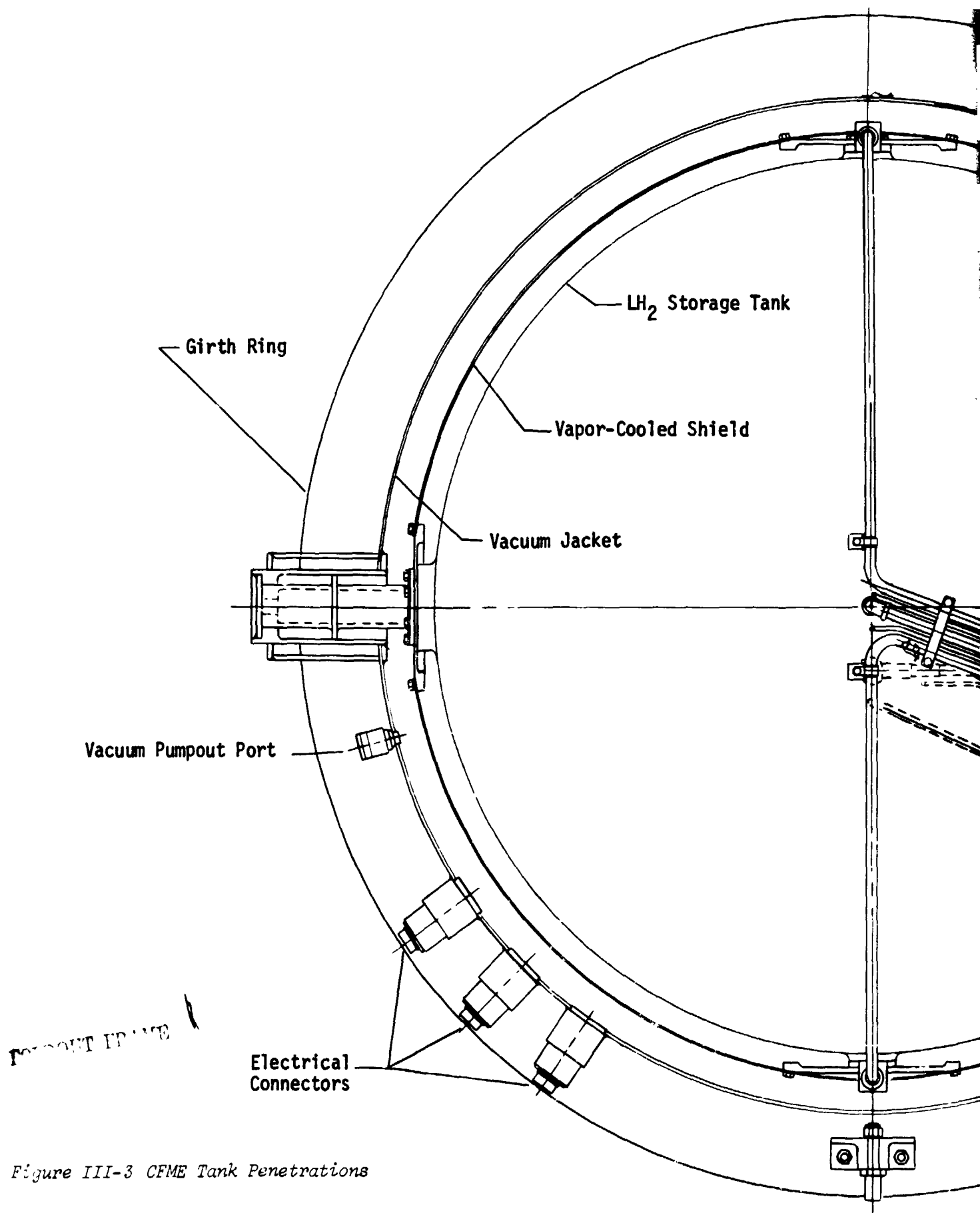
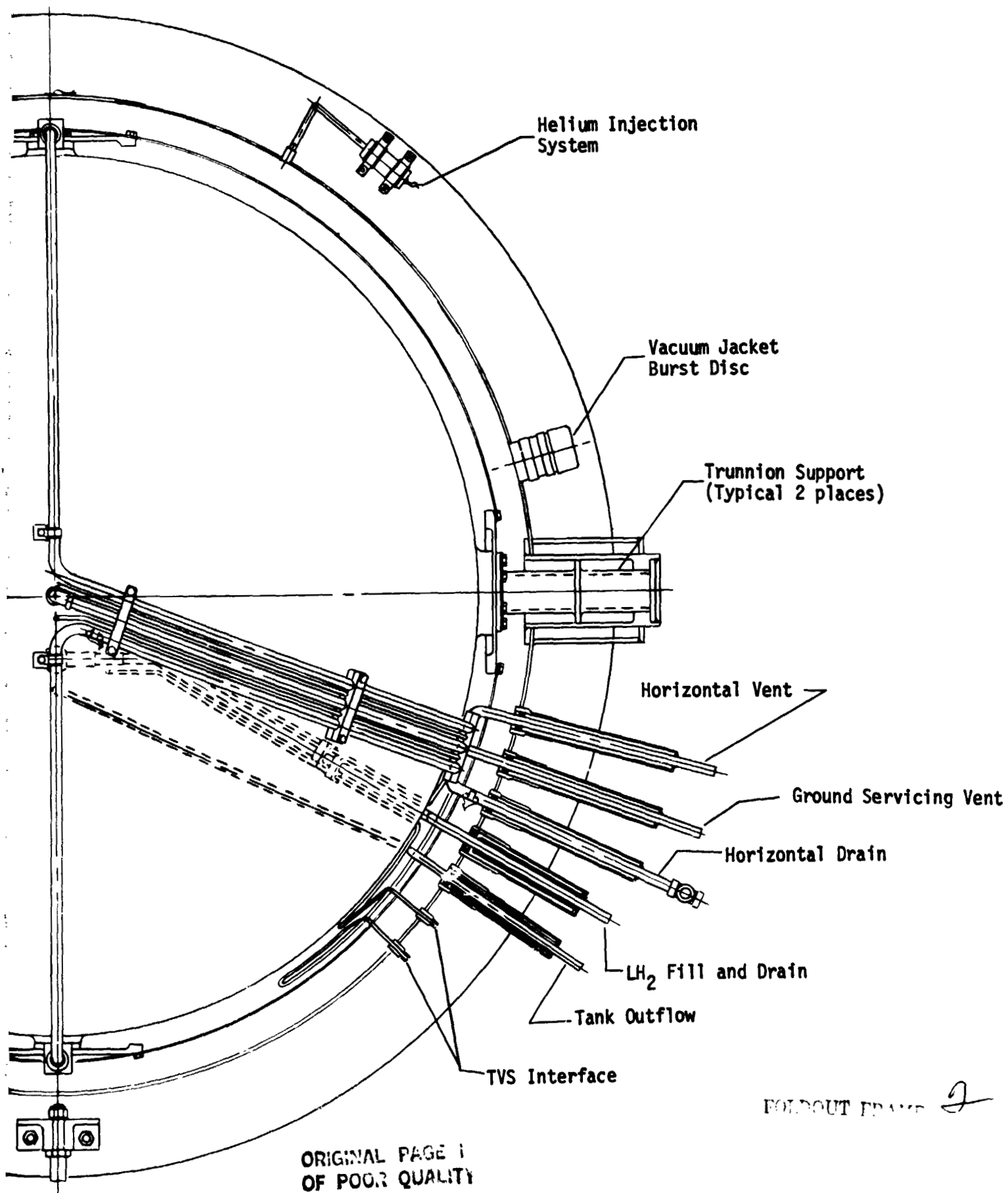
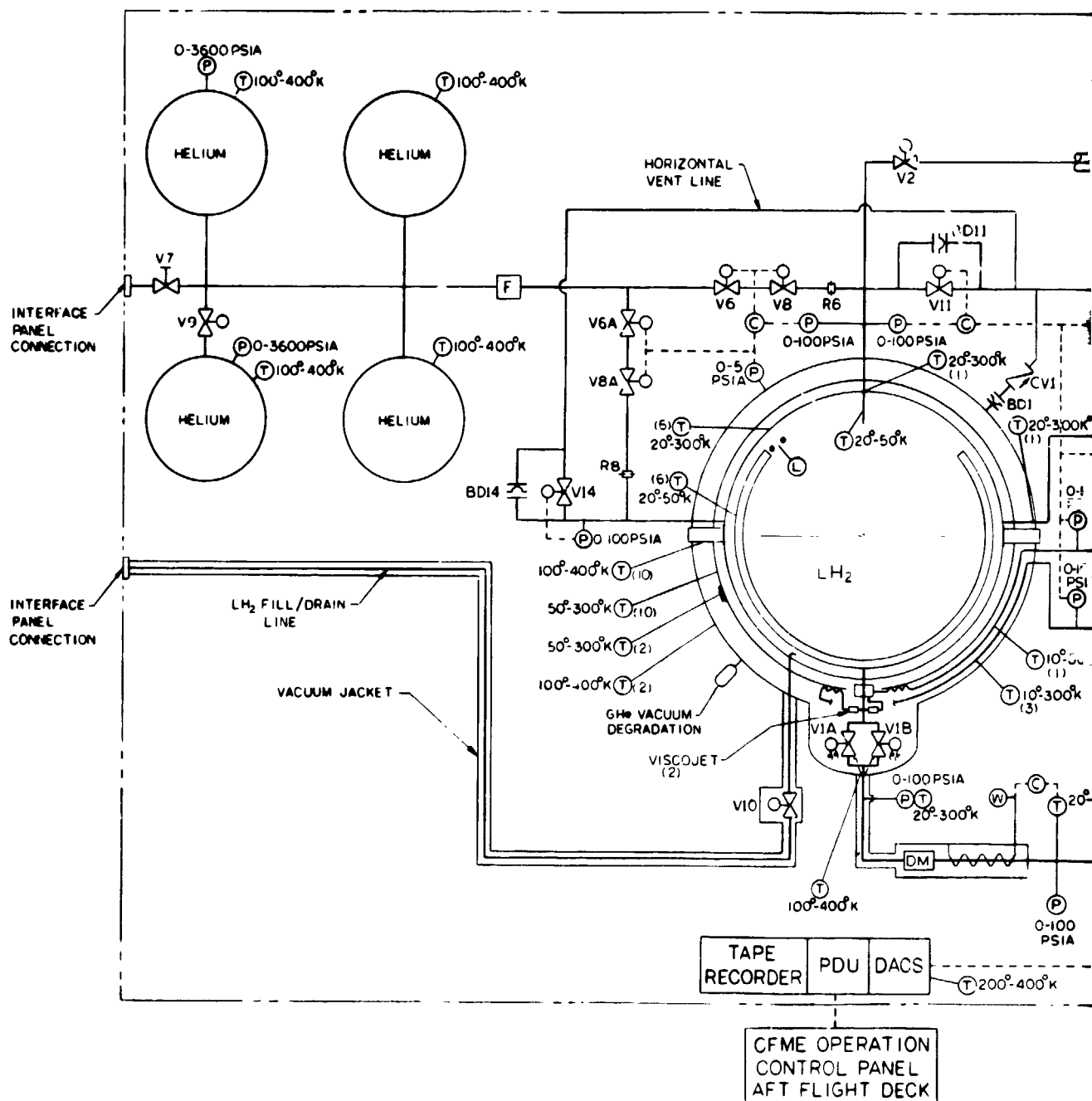
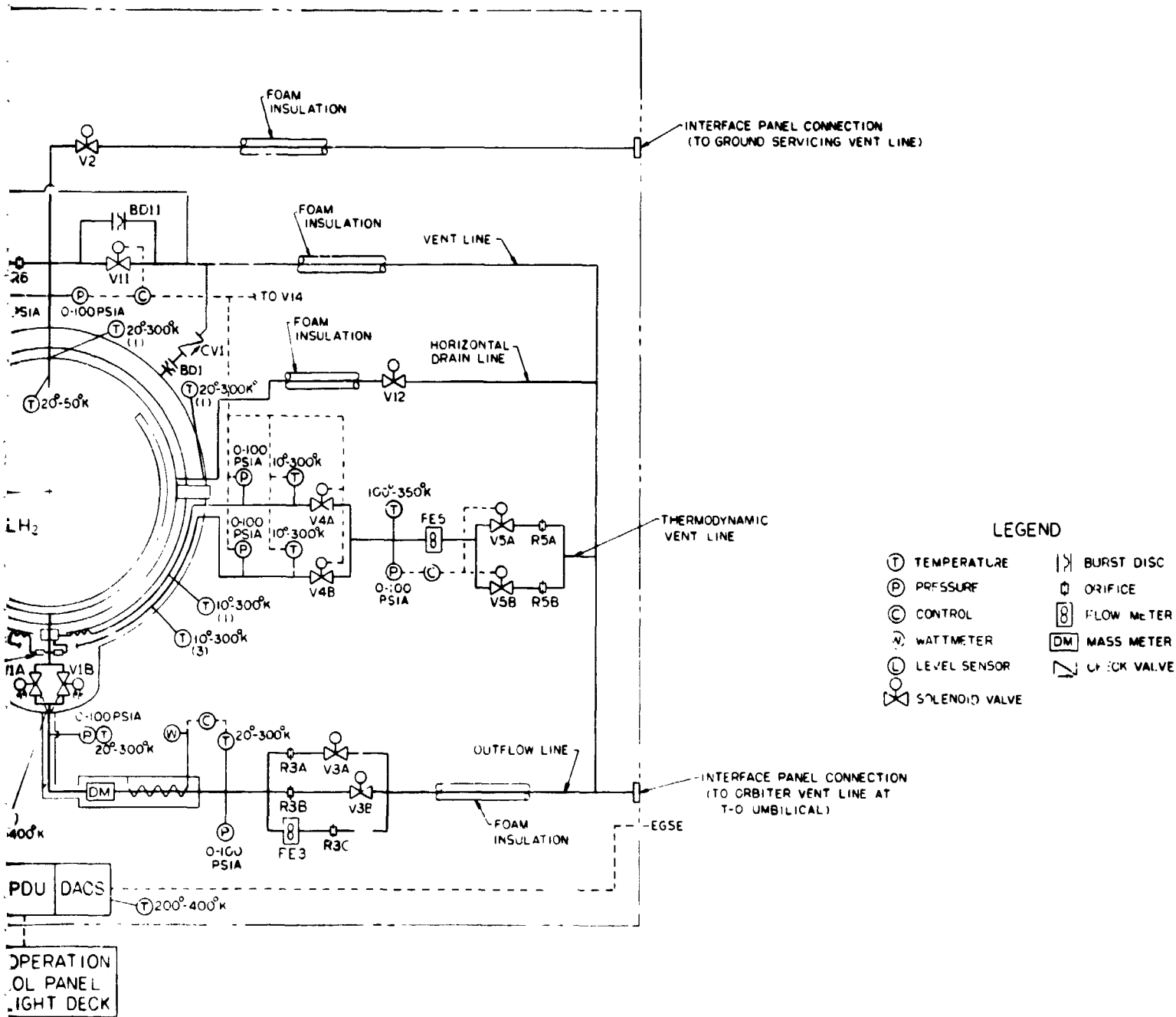


Figure III-3 CFME Tank Penetrations



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2

Figure III-4 CIME Schematic

helium-filled cylinder is mounted to the VJ girth ring to permit the injection of a small amount of helium into the vacuum annulus to increase the heat flux to the hydrogen tank. Heat fluxes as high as  $63 \text{ W/m}^2$  ( $20 \text{ Btu/hr-ft}^2$ ) can be accommodated.

- o Tank Assembly Thermal Control System. A spherical vapor-cooled shield (VCS) is located concentrically between the liquid hydrogen tank and the vacuum jacket. A thermodynamic vent system (TVS) with heat exchangers that cool the shield, and multilayer insulation mounted on the shield, accomplish active and passive thermal control.
- o Experiment Thermal Control System. Externally mounted thermal blankets will be installed over thermally sensitive areas in order to limit temperature variations. A protective thermal shroud covers the experiment and limits solar heat input.
- o Pressurization System. Four pressurant spheres, initially filled with helium to a maximum pressure of  $21600 \text{ kN/m}^2$  ( $3135 \text{ psia}$ ) at  $29^\circ\text{C}$  ( $85^\circ\text{F}$ ) together with control valves maintain the liquid hydrogen tank pressure at  $379 \text{ kN/m}^2$  ( $55 \text{ psia}$ ) during LH2 expulsion under normal experiment or abort conditions and provide gas for LH2 tank inerting.
- o Data Acquisition and Control System (DACS). The data acquisition portion of this system includes the instrumentation to measure the CFME performance, provision for signal conditioning and processing, and a tape recorder to record data during launch and throughout the on-orbit portion of the mission. The control portion of this system consists of dedicated instrumentation to monitor critical parameters, and a microprocessor to automatically monitor and sequence the operations and transmit critical parameters.

Each of these experiment elements is discussed in greater detail in the following paragraphs.

1. Liquid Acquisition Device (LAD). The liquid acquisition device is the key element for subcritical storage and supply of the liquid hydrogen. This device provides the means of expelling gas-free liquid from the tank in the low-g operational environment. The device makes use of the surface tension forces of the liquid to position the liquid within the tank and to prevent gas from entering the tank outlet.

Liquid acquisition devices, using the surface tension forces produced by the liquid, can take many forms. For this application, the surface tension forces are produced at the interface between the gas and liquid within the pores of a fine-mesh screen. The configuration of the LAD is shown in Figure III-5. It has four channels manifolded at the outlet. The channels are truncated near the top of the tank, terminating the flow passage. The sheet metal continues so the four channels join at the top of the tank. The side of the channel facing the tank wall is covered with screen. The channels are

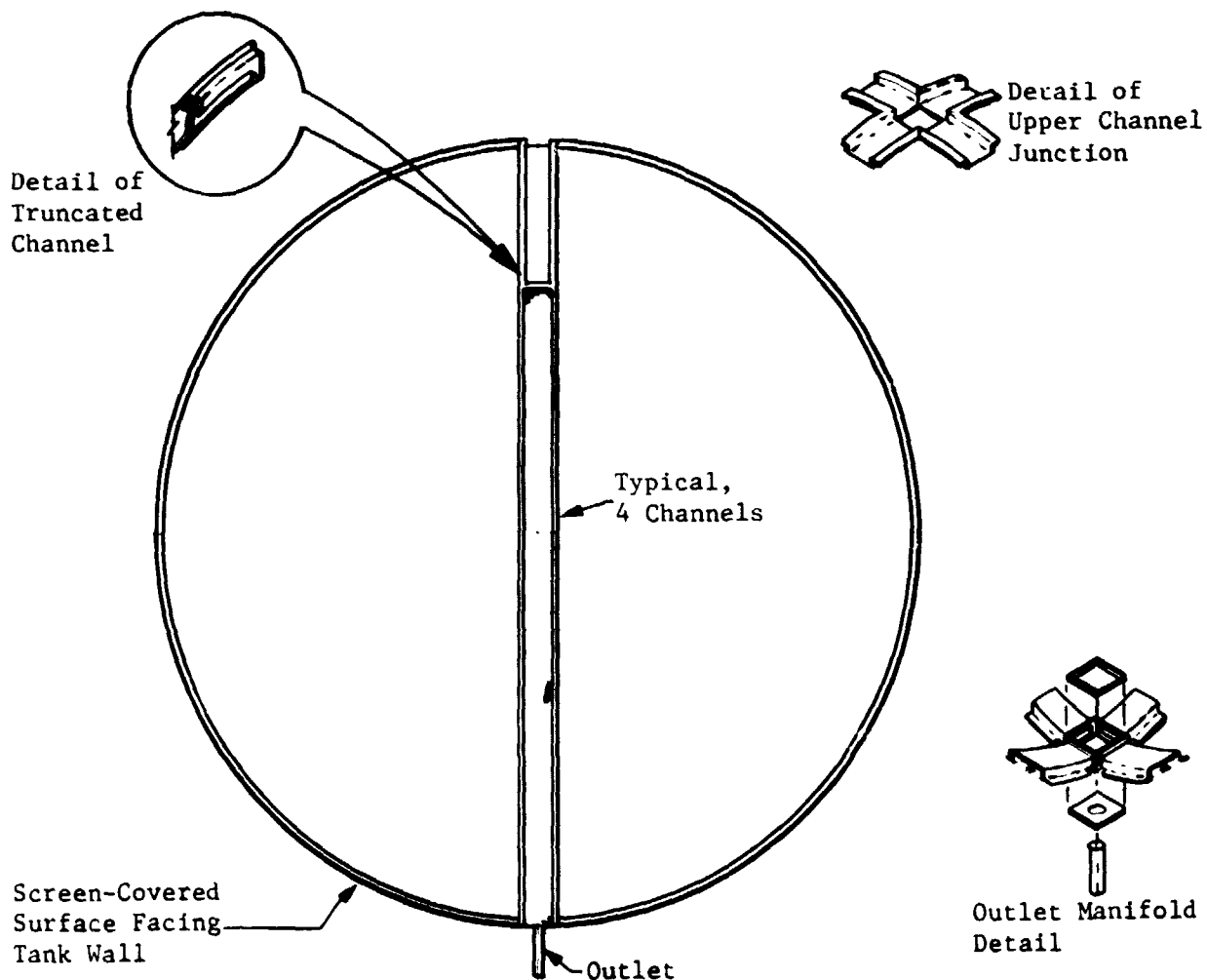


Figure III-5 Liquid Acquisition Device Configuration

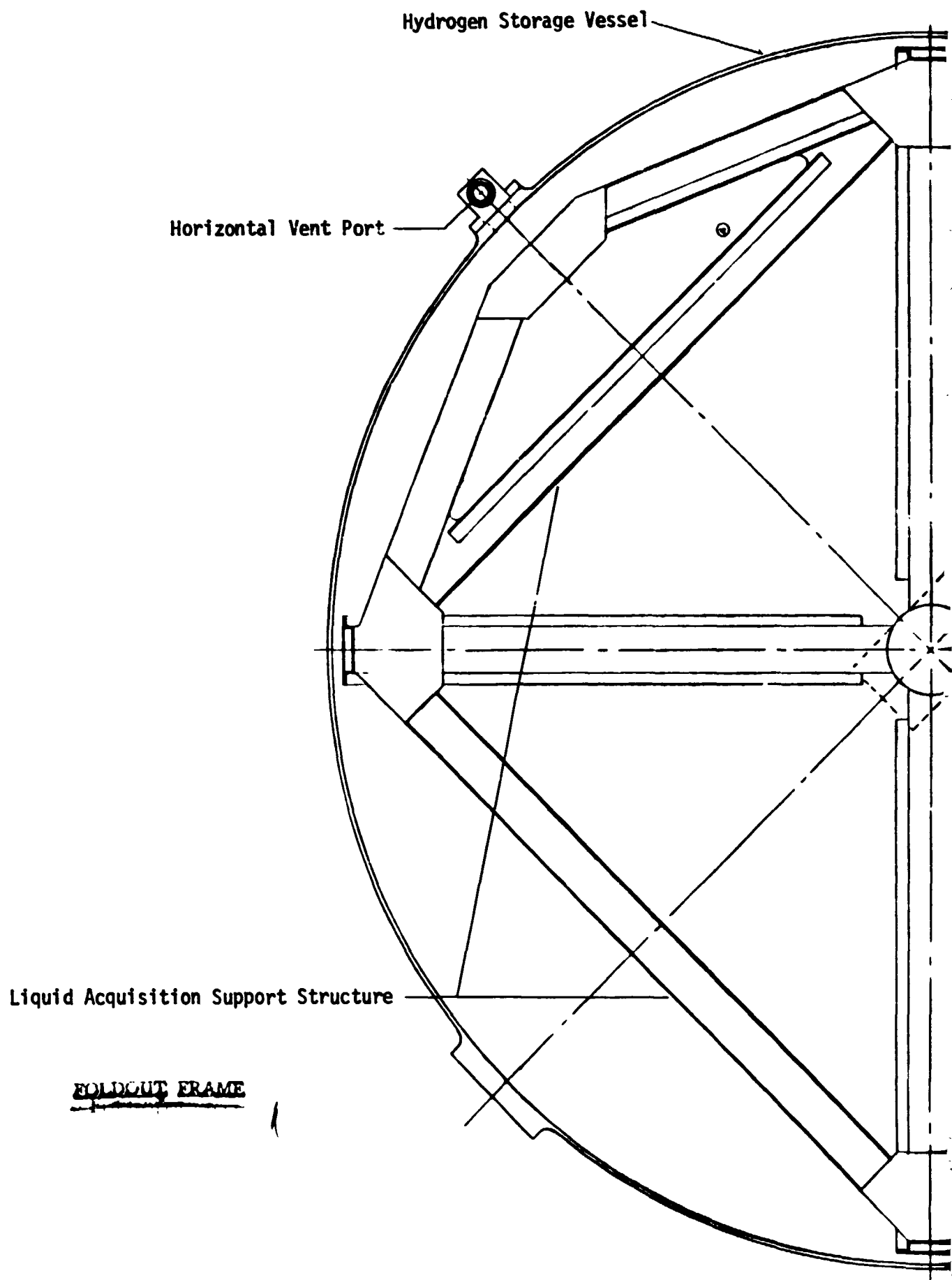
truncated to prevent exposure of the screen to the ullage during the launch phase of the mission. The support structure for the LAD is shown in Figure III-6.

The channels of the device are filled with liquid as the tank is loaded. Consequently, the interior surface of the screen will be in contact with liquid. The outer surface of the screen will be exposed to either gas or liquid depending on the volume of liquid in the tank and its orientation. When liquid is located on both sides of the screen, liquid can flow freely through the screen, opposed only by friction due to the screen wires. When the outside surface of the screen is exposed to gas, the interface between the gas and liquid within the screen pores permits the device to function. The normal tendency is for the pressure within the channel to be less than the ullage pressure, so the pressure differential is acting to force gas into the channels. Surface tension forces oppose the entry of gas into the channels. A capillary pressure differential is produced that is a function of the liquid surface tension and the curvature of the interface. For a wetting liquid, which is the case for liquid hydrogen, the curvature of the interface and the capillary pressure reach a maximum when the interface radius is equal to the pore radius. Further increases in the interface radius produce a curvature decrease and a corresponding decrease in the capillary pressure.

Rather than attempt to measure the pore radius, the maximum capillary pressure of a screen pore can be directly measured. The screen is oriented horizontally and covered with a layer of liquid. It is pressurized from below and the pressure differential necessary to cause gas to bubble through the screen (the "bubble point") is measured. As long as the pressure differential across the screen is less than its bubble point (the maximum capillary pressure), gas cannot penetrate through the screen. The hydrostatic, dynamic, and viscous forces acting on the liquid within the channels produce the pressure differential across the screen. By properly selecting the screen mesh and the configuration of the channels, the pressure differential will be less than the bubble point, and gas-free outflow of liquid from the tank can be maintained because the channels are directly connected to the tank outlet.

2. Liquid Hydrogen Tank. The liquid hydrogen storage vessel is a 106-cm (41.7-in) diameter assembly fabricated from 6061-T6 aluminum. The assembly consists of two hemispherical-shaped domes which are welded to an equatorial





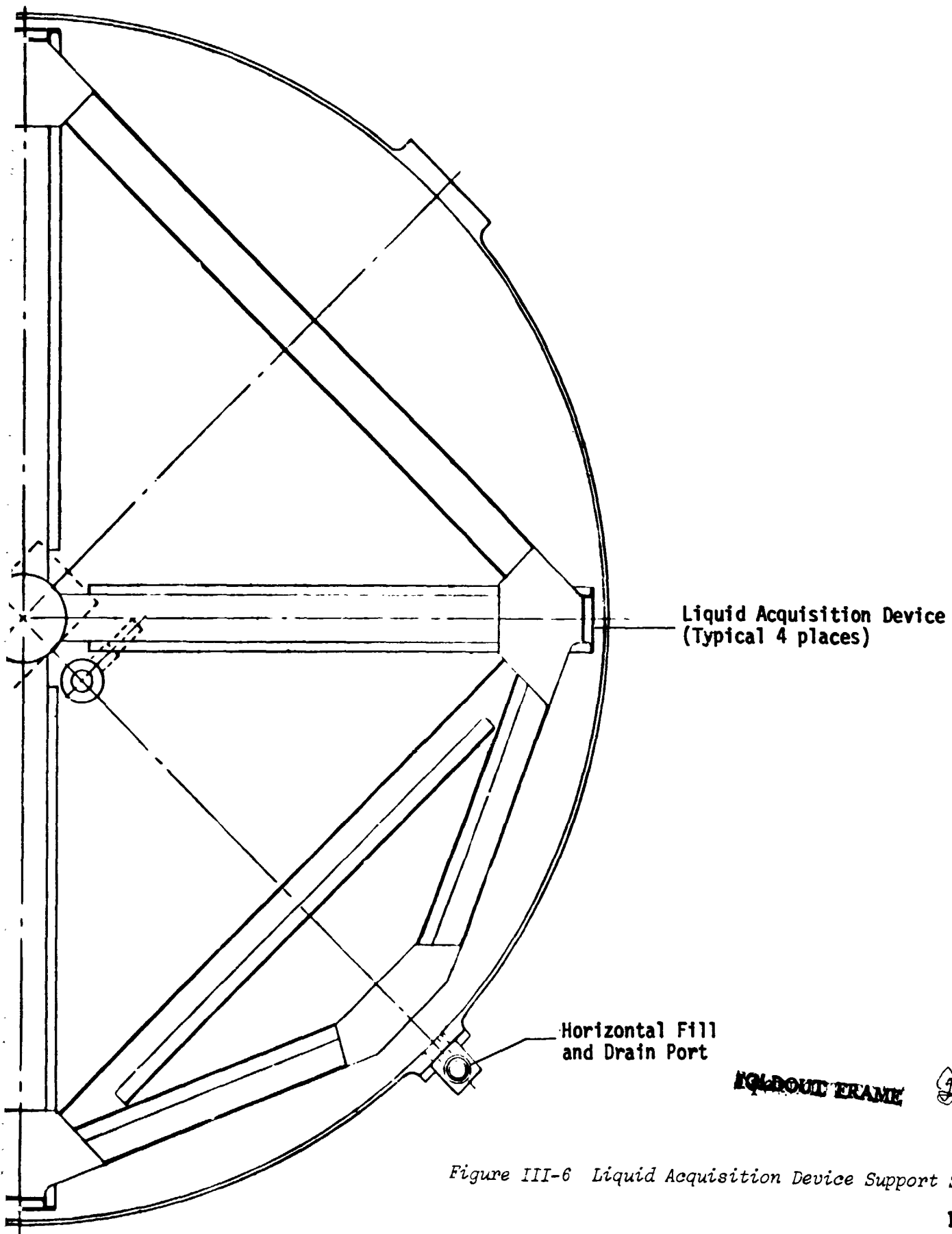


Figure III-6 Liquid Acquisition Device Support Structure

attachment ring. The dome wall thicknesses are a minimum of 0.155-cm (0.061-in) with increased thickness at the poles and at the attachment ring interface of 0.508-cm (0.20-in) and 0.318-cm (0.125-in) respectively. The ring wall thickness is a minimum of 0.368-cm (0.145-in) with increased thickness at the trunnion interface locations. These wall thicknesses resulted from the 2.5 safety factor imposed on the design yield point as well as a requirement to meet a  $103 \text{ kN/m}^2$  (15.0 psi) collapse pressure.

The storage tank contains the liquid acquisition device which interfaces at the poles ( $\pm$  X-axis) of the sphere. The outlet end is fixed by a welded stainless steel-to-aluminum transition tube between the acquisition device and vessel. The vessel is supported from the vacuum jacket girth ring by two S-glass/epoxy trunnions which interface with the attachment ring ( $\pm$  Y direction) of the sphere.

The tank is also tied to the vacuum jacket at the outlet end of the sphere through a composite torsion member. This tie is required to support the LAD outlet valve and line assembly, and to increase the supported torsional frequency of the storage vessel above the 35 Hz requirement.

3. Vacuum Jacket/Girth Ring/Trunnion Supports. The vacuum jacket and girth ring are fabricated from 6061-T6 aluminum. The girth ring has a diameter of 116.1-cm (45.7-in), and is a forged and machined channel section. The ring is positioned in the Y-Z plane when mounted on the Spacelab pallet. Sizing of the girth ring was primarily based on meeting the 35 Hz fundamental mode requirement.

The girth ring interfaces with the base support frame through two bipod struts and a shear support on the -Z axis. The girth ring also interfaces with the storage vessel through two S-glass/epoxy trunnions. The trunnion mount configuration is shown in Figure III-7. This design resulted from a trade study considering both the thermal requirements and the structural design as driven by fatigue for seven-mission life. One trunnion is fixed, and adjusted to the proper position prior to final closeout welding of the support tube assembly by a threaded and vented fitting. The other end is free to allow for contraction and expansion of the pressure vessel/trunnion assembly.

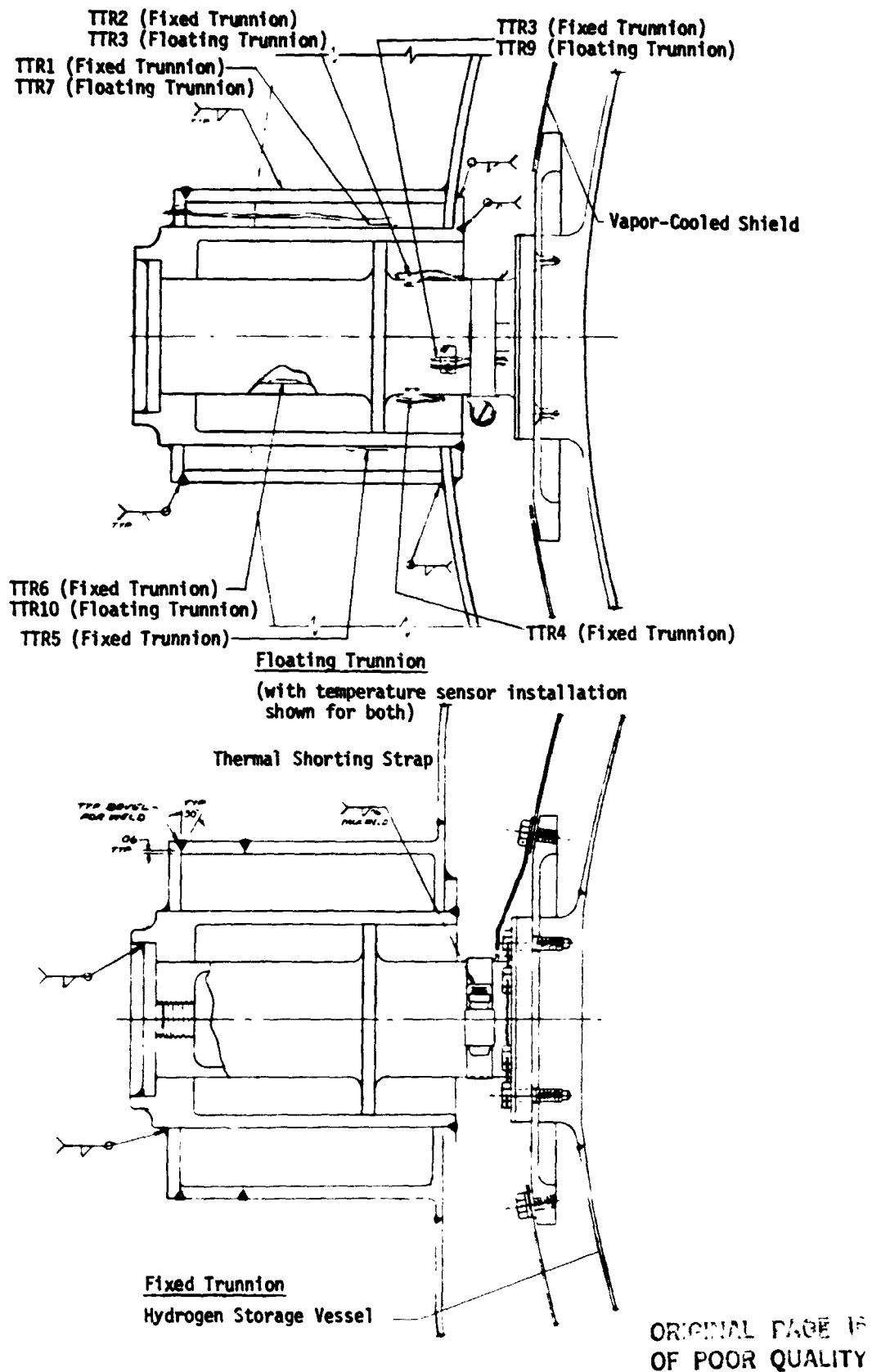


Figure III-7 Trunnion Mounting Configuration

The vacuum jacket consists of two 6061-T6 aluminum hemispherical domes which are welded to the girth ring. The shell membrane thickness is 2.79-mm (0.11-in). This thickness provides a safety factor of 1.5 against a collapse pressure of  $101 \text{ kN/m}^2$  (14.7 psia).

A helium vacuum degradation system is connected to the vacuum annulus through the vacuum jacket. It consists of a helium storage cylinder of  $19 \text{ cm}^3$  ( $1.15 \text{ in}^3$ ) which is isolated from the vacuum annulus by a pyrotechnic device which is armed from the Aft Flight Deck just prior to usage. Activation of the device is accomplished by DACS software at the appropriate time in the mission. A calculated mass of helium will be loaded into the cylinder so that it will impart a heat flux of up to approximately  $63 \text{ W/m}^2$  ( $20 \text{ Btu/hr-ft}^2$ ) to the storage tank when activated. Pressure in the vacuum annulus will increase from approximately  $1 \times 10^{-6}$  torr up to a maximum of  $96 \text{ N/m}^2$  (0.014 psia) depending upon the quantity of helium loaded and injected in the annulus. Changes in performance characteristics of the thermodynamic vent system, insulation, and liquid acquisition device will be evaluated.

4. Tank Assembly Thermal Control System. The thermal control system of the hydrogen tank assembly consists of a vacuum jacket, thermodynamic vent system (TVS), vapor-cooled shield (VCS) and multilayer insulation (MLI). The vacuum jacket surrounds the hydrogen storage tank, permitting the annular space to be evacuated. The vacuum jacket is essential to the tank thermal control during ground operations and launch. The girth ring of the vacuum jacket also provides mounting points for the tank assembly and protection of the MLI.

The TVS uses liquid hydrogen provided by the liquid acquisition device to control tank pressure. The hydrogen flows through two heat exchangers, each having an orifice that reduces the hydrogen temperature. These heat exchangers are mounted to the tank penetrations and the vapor-cooled shield located concentrically between the tank and the vacuum jacket. The MLI is mounted on the vapor-cooled shield.

a. Thermodynamic Vent System. The liquid acquisition device does not control the location of the ullage within the tank in a low-g environment, so venting of the tank in the conventional manner is not possible. The TVS provides the means for relieving the tank pressure increase due to heat input.

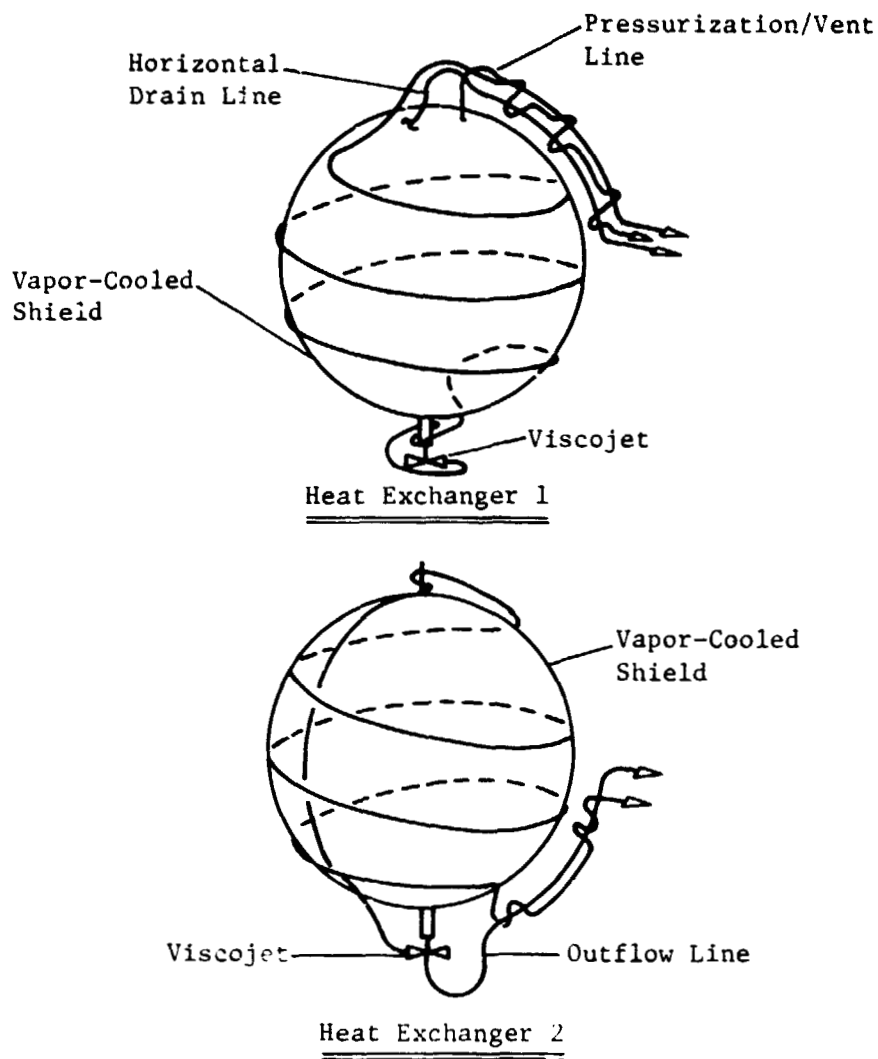
In the TVS, liquid cryogen is withdrawn from the tank through use of the liquid acquisition device. The vented liquid is used as a refrigerant to reduce the net heat input to the tank. This is accomplished by routing the vent fluid through two heat exchangers, which remove heat from the tank and intercept heat entering through the insulation and along other conduction paths. The pressure in the heat exchanger is made as low as practical (but above the triple point pressure to prevent solidification), which significantly increases the capability of the vent system to absorb heat. Reducing the pressure also provides a much lower average sink temperature, reducing heat exchanger conduction requirements.

The additional cooling capacity of the vent gas leaving the VCS is used to reduce heat leak along the fill, vent, dump, and outflow lines. This is achieved by routing the TVS vent lines in bundles with these tubes between the inner pressure vessel and the vacuum jacket with sufficient thermal coupling to provide the required heat exchange (see Figure III-7). The two heat exchanger configuration of the TVS shown in Figure III-8 increases the variability of the vent rate and provides redundancy of components. Heat exchanger 1 (HX1) is configured in a bottom-to-top direction and is sized to remove 60-80 percent of the tank heat leak. This heat exchanger provides cooling to the bottom as a means for maintaining the outlet end of the tank at a lower temperature than the top. When the TVS heat exchanger is operating, the heat input due to tube and leadwire conduction is reduced from 3.3 W (11.2 Btu/hr) to 0.8 W (2.9 Btu/hr). The flow of the other heat exchanger (HX2) is in the top-to-bottom direction, providing a means for removing about 200 percent of the predicted heat input (heat input without heat exchanger 1 operations).

For each of the heat exchangers, liquid is withdrawn from the tank outlet line and directly flows through a Viscojet\* multiorifice flow restrictor. The Viscojet serves to meter the vent flow rate while reducing pressure from the maximum of 380 kN/m<sup>2</sup> (55 psia) to a low pressure in the range of 14 to 56 kN/m<sup>2</sup> (2 to 8 psia).

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\*Trademark, The Lee Co.



*Figure III-8 TVS Heat Exchanger Configuration*

At the downstream side of the flow restrictor, 15 to 25 percent of the liquid will have vaporized and the temperature will be in the range of 15 to 18<sup>0</sup>K (27 to 32<sup>0</sup>R). For HX1 (bottom-to-top), this cold fluid is routed through the first stage of the heat exchanger, which cools the outflow line and valves, and the fill and drain line as the primary means for maintaining the outlet region below saturation temperature. The heat exchanger tube is then routed around the vapor cooled shield to apply an equal length of tube to equal areas of the shield, with a total length of approximately 12.2 m (40 ft), and the direction of flow being from bottom-to-top. On leaving the VCS

near the top of the tank, the HX1 tube is routed in a bundle with the pressurization/vent line and the horizontal drain line under the VCS to the equator of the tank and then outward through the vacuum jacket girth ring.

Heat exchanger 2 (HX2) begins with a Viscojet also connected to the tank outlet line. It is then routed inside the VCS directly to the top of the tank with minimal thermal contact with the VCS. At that point, the tube is wrapped over both the pressurization/vent, and the horizontal drain lines to intercept heat flow through these lines and remove heat directly from the top of the tank. From there it is routed on the VCS in the same manner, but in the opposite direction, as the first heat exchanger. On leaving the VCS, HX2 is bundled with the fill and drain line as it is routed under the VCS to the tank equator and then through the girth ring of the vacuum jacket. The liquid outflow line is routed along with the fill and drain line and heat exchanger tube. In all instances, the tube bundles are separately insulated with MLI to isolate them from the VCS and the primary tank multilayer insulation system.

Flow in the two heat exchangers is controlled by on-off latching solenoid valves actuated by the DACS. The two heat exchanger circuits tee into a common line downstream of the selector valves where the vent fluid is warmed by coupling with the environment, and metered. Finally, the fluid is exhausted to atmosphere or space through either or both of two valve-orifice assemblies connected in parallel. The selector valves are operated by the DACS to regulate both tank pressure and the temperature difference between the poles of the storage tank. The second pair of valves are controlled to maintain a backpressure in the active heat exchangers at  $35 \pm 20 \text{ kN/m}^2$  ( $5 \pm 3 \text{ psia}$ ).

When the control valves are closed, the rise of pressure within the heat exchangers could cause a reversal of the flow, pushing gas into the liquid acquisition device. This situation is avoided by activating the TVS when the pressure within the heat exchangers reaches a predetermined percentage of tank pressure.

b. Multilayer Insulation System. The MLI configuration consists of  $3.8 \times 10^{-3} \text{ mm}$  (0.15-mil) thick double aluminized Mylar (DAM) radiation shields separated by two Dacron B4A net spacers, assembled to a layer density of 24



reflectors/cm (60/in). When coupled with a budget for heat input due to conduction along pipes, leadwires and supports of 5.94 W (20.3 Btu/hr), the optimum insulation thickness is made up of 75 layers of DAM and 152 net spacers. The average vent rate (HX1 only) for this configuration is 0.023 kg/hr (0.05 lbm/hr).

The method of fabricating the insulation is to assemble gore sections over a mandrel of the proper size and shape. It is assembled with closely spaced threads tied between structural nets. Thickness of the blanket is controlled by mechanically gaging the length of the thread. A small preload helps to improve dimensional stability. Diagonal threads are installed in the direction of the primary load on the blanket to limit slippage and compression of the blanket during boost loads. A hot needle is used to penetrate the Mylar foils through which the threads pass. This technique provides a reinforced hole with much greater strength than the torn opening made by a cold needle.

The aluminized Mylar reflector material is perforated for purging and to assure evacuation in space. The perforated area is designed to allow flow of purge gas and to permit evacuation in a reasonable time without stressing the panels due to contained gas. Attachment of the insulation blankets is by means of snap and curtain fasteners attached to Dacron ribbons which, in turn, are fastened across the full length or breadth of the panel. These fasteners are located on all sides of each blanket, with mating pins bonded to the vapor-cooled shield. At frequent intervals (approximately 0.3 m) over the surface of the blanket, Velcro pile strips are bonded. Velcro hook strips are mounted on the vapor-cooled shield at right angles to permit engagement with small alignment errors. These strips are secured in place with small strips of Mylar tape at appropriate intervals. Inner and outer structural nets of adjacent panels are stitched together over the full length of the butt joints.

5. External Thermal Control System. A preliminary analysis, discussed later in Chapter V, Section B3, indicated the need for a thermal shroud to be draped over the entire experiment package to reduce the maximum temperatures and raise the minimum temperatures to levels acceptable for all CFME components. Using the assumptions for a thermal environment inside the cargo bay specified earlier in Table II-6, the expected temperature extremes exceeded the design

values for some components. The lack of a specific mission assignment including identification of nearby companion payloads, precludes being able to reduce this wide temperature band and more accurately define realistic temperature profiles. The use of a shroud, however, simplifies considerably the design for thermal excursions (i.e. need for heaters and/or cold plates).

The experiment package may still require special thermal conditioning but that cannot totally be evaluated until better mission parameters are available. A shroud of 30 layers of double aluminized-Mylar and nylon net spacers is adequate to control the temperature extremes per the thermal cycling defined in Table II-6. The thermal shroud also maintains the helium in the pressurant tanks at a high enough temperature so there is a sufficient supply at a high enough temperature (and therefore energy) level to adequately expel and inert the hydrogen storage tank under worst case environmental conditions.

6. Pressurization System. The pressurization system provides helium gas for liquid expulsion from the tank and for purging of residual hydrogen (tank inerting) after expulsion is complete. Cost and size trade studies indicated that a preferred approach for providing helium storage would be to use off-the-shelf 6Al-4V titanium spheres with a nominal inside diameter of 34.8-cm (13.7-in) and an operating pressure of 21600 kN/m<sup>2</sup> (3135 psig). Each sphere holds 0.69 kg (1.51 lbm) of helium. A total of four of these storage spheres is required to satisfy the expulsion and purging requirements. The spheres are covered with one inch of MLI for thermal protection in the adverse hot payload environment, and to guarantee adequate pressure for meeting mission objectives when in the adverse cold environment. One of the pressurant spheres and a representative mounting configuration are shown in Figures III-9 and III-10, respectively.

One of the helium spheres is isolated from the others by a separate solenoid valve, V9. This approach was selected to provide redundancy and operational flexibility for contingency conditions in the event of valve malfunction and premature discharge of helium. With this configuration, one tank of helium is retained until the end of the mission to accomplish expulsion and inerting of the hydrogen storage tank.



Figure III-9 Helium Storage Sphere

FIG. 1

FIG. 2

VIEW A-A

Strap Assembly

Helium Sphere Support Structure

Fiberglass Composite Saddle

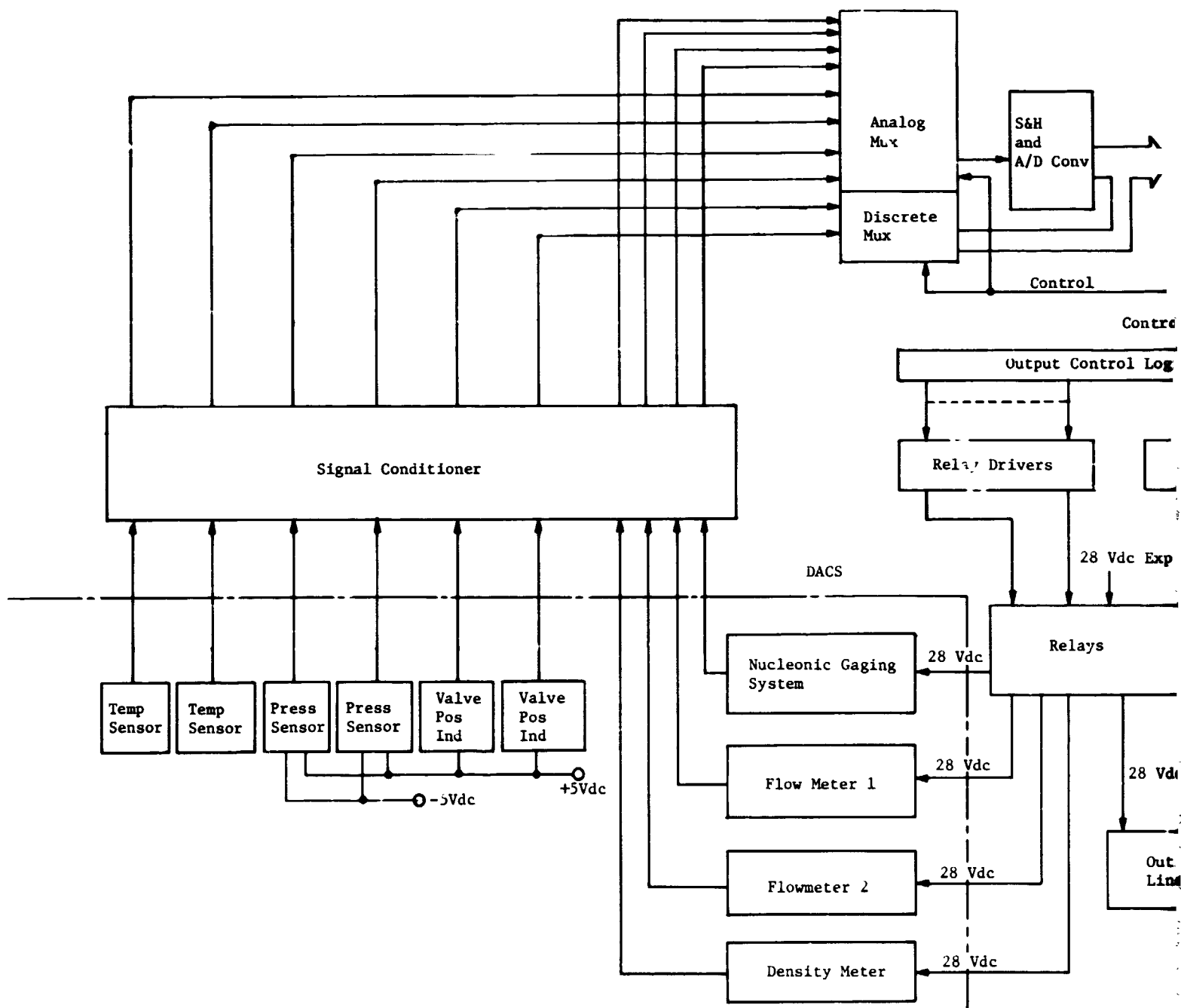
III-19

Pressure regulation is accomplished with two sets of two valves in series. One set functions when the experiment is in the vertical (launch) attitude while the other operates when the experiment is in the horizontal (landing) configuration. This arrangement was selected because of the relatively high cost of a flight-qualified regulator that could meet the diverse helium flowrate requirements. The first valve is opened to admit the high pressure helium to a fixed volume of  $15.8 \text{ cm}^3$  ( $1 \text{ in}^3$ ) between the valves. After closing the first valve, the second valve is opened, allowing blow-down of the volume between valves into the tank. On orbit either set of valves can be used (however, V6 and V8 are prime; see Figure III-4). By monitoring the valve position indicators, a leg with a failed valve can be detected and the other leg can be used. The valve cycling sequence includes the checking of the valve position, a period for stabilization, and comparison of the set point with the tank pressure, all performed by the experiment computer (DACS).

7. Data Acquisition and Control System. The Data Acquisition and Control System (DACS) is the electronics subsystem of the CFME, providing automatic experiment operation, which minimizes involvement of the Payload Specialist. Its functions are to collect data from the experiment for evaluation and control, and to operate the electromechanical components of the CFME in a programmed manner.

The DACS consists of a microprocessor controller, tape recorder, circuits to interface with the experiment valves, signal conditioning and processing for the experiment instrumentation, and two power distribution units (PDU). A block diagram of the DACS showing its interfaces with the CFME flight hardware, is presented in Figure III-11.

Control of the experiment operations, from the loading of liquid hydrogen at the launch pad through termination of the experiment on orbit, is under primary control of the microprocessor. The DACS contains the microprocessor, memory, all the circuitry required to condition and digitize the measurements, and valve and relay drivers for the control functions.



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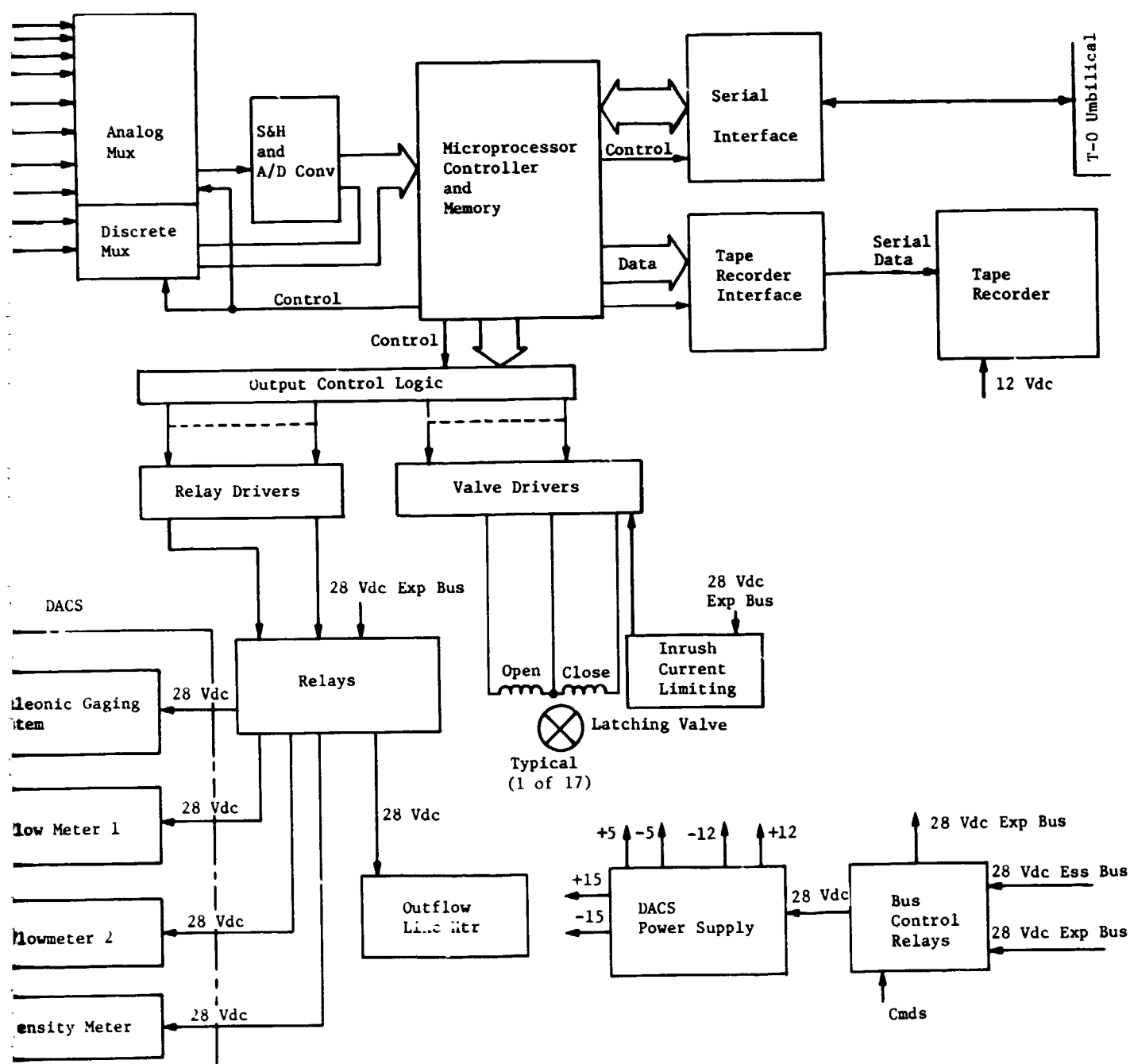


Figure III-11 DACS Block Diagram

The microprocessor executive program includes a number of subroutines that control the various experiment operating modes. These modes are the thermodynamic vent system (TVS) mode, the various outflow modes, abort modes, and data collection modes. The mode sequence will be programmed for automatic operation by the experiment computer. Mode control with the DACS GSE (designated as EGSE) will also be provided through the T-0 umbilical to accomplish loading and offloading while on the pad. The Payload Specialist has the capability to change the experiment operation through switch actuation control of the DACS from the CFME Operation Control Panel (discussed in greater detail in Section B, Paragraph 4).

The first operating mode is the data collection mode on the launch pad. The EGSE link through the T-0 umbilical is used for data collection on the launch pad. The TVS mode is also enabled by the EGSE link through the T-0 umbilical. The microprocessor controls the tape recorder and the TVS loop simultaneously. The TVS control is implemented in the DACS by monitoring the tank pressure and the heat exchanger pressures and temperatures. A control algorithm, based on empirically derived coefficients relating the tank pressures and heat exchanger pressures and temperatures, is stored in the DACS memory, and used to regulate the TVS valves for tank pressure control. These coefficients will be obtained during the ground test program.

The outflow modes are also programmed into the DACS sequence. The microprocessor turns on the outflow line heater, controls the helium pressurization system, and opens the tank outlet valves. The outflow line liquid and gas flowmeters are turned on by the microprocessor during this mode. The outflow modes are further controlled to obtain the required flow rates and thermodynamic states corresponding to the mission sequence of events. The experiment computer is programmed to send the proper commands to accomplish the sequence of operations. The timekeeping function is handled by a timer circuit card in the DACS. Outflow is terminated prior to the end of the mission by the Payload Specialist.

The abort mode can be initiated by the Payload Specialist using a switch on the CFME Operation Control Panel. The microprocessor sets the valves to the proper position for outflowing the liquid hydrogen with the pressurization system activated. The outflow line heater is turned off. An abort backup is



available and is initiated from the Operation Control Panel under emergency conditions. The abort backup does not use microprocessor control, but rather direct valve control from the Operation Control Panel.

A DACS system available from SCI Systems, Inc., Huntsville, Alabama, was selected as the CFME baseline. The DACS is shown in Figures III-12 and III-13. Their DACS is designed and fabricated in modular fashion, enabling a system such as that envisioned for the CFME to be built from essentially "off-the-shelf" hardware. The DACS includes the microprocessor, central processing unit (CPU) and memory cards, designed around the Intel 8080 microprocessor. Memory is expandable by adding cards. The system cards include all those required for data acquisition except the signal conditioner card. The latter card is a new development but should not present any technical design risk. Circuit design of this card is straightforward.

The CPU, memory, Input/Output and other logic and low level signal cards are housed in one case. A second case houses the power control, relays, valve drivers and decoder logic. This separation of logic and power circuits is desirable to prevent electromagnetic interference from the power circuits, causing errors in the control logic.

The Spacelab Payload Accommodations Handbook, SPAH SLP/2104, delineates the requirements for the electromagnetic compatibility (EMC) of experiments. These include limits for conducted emissions on power, and the electromagnetic environment for the experiment. The CFME electronics was designed to meet the EMC requirements and to operate without malfunction in the specified environment. Because the CFME has a microprocessor and large current loads in the same system, extra care was exercised in the housing and cabling design. Some of the considerations were: in-rush current caused by valve and heater operations; power supply line filtering; adequate sizing of the grounding board for fault current protection in potentially explosive environments; signal and power wires in separate cable bundles; and proper shielding of signal wires.

The program for the microprocessor is permanently stored in programmable read-only memory (PROM). About 3K bytes of PROM are required to store all the CFME program. An extra 1K byte will provide for future expansion. The random

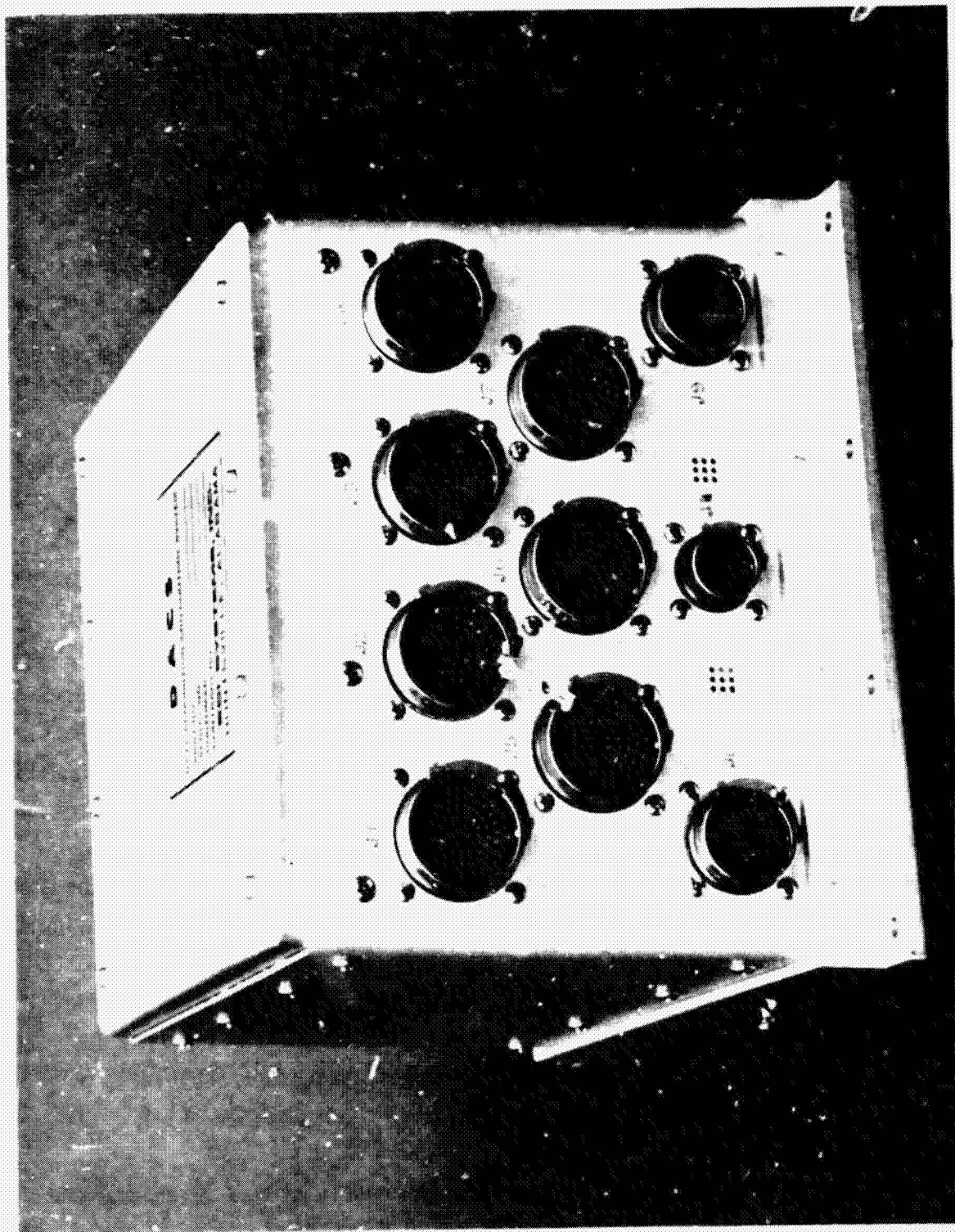


Figure III-12 Assembled DACS

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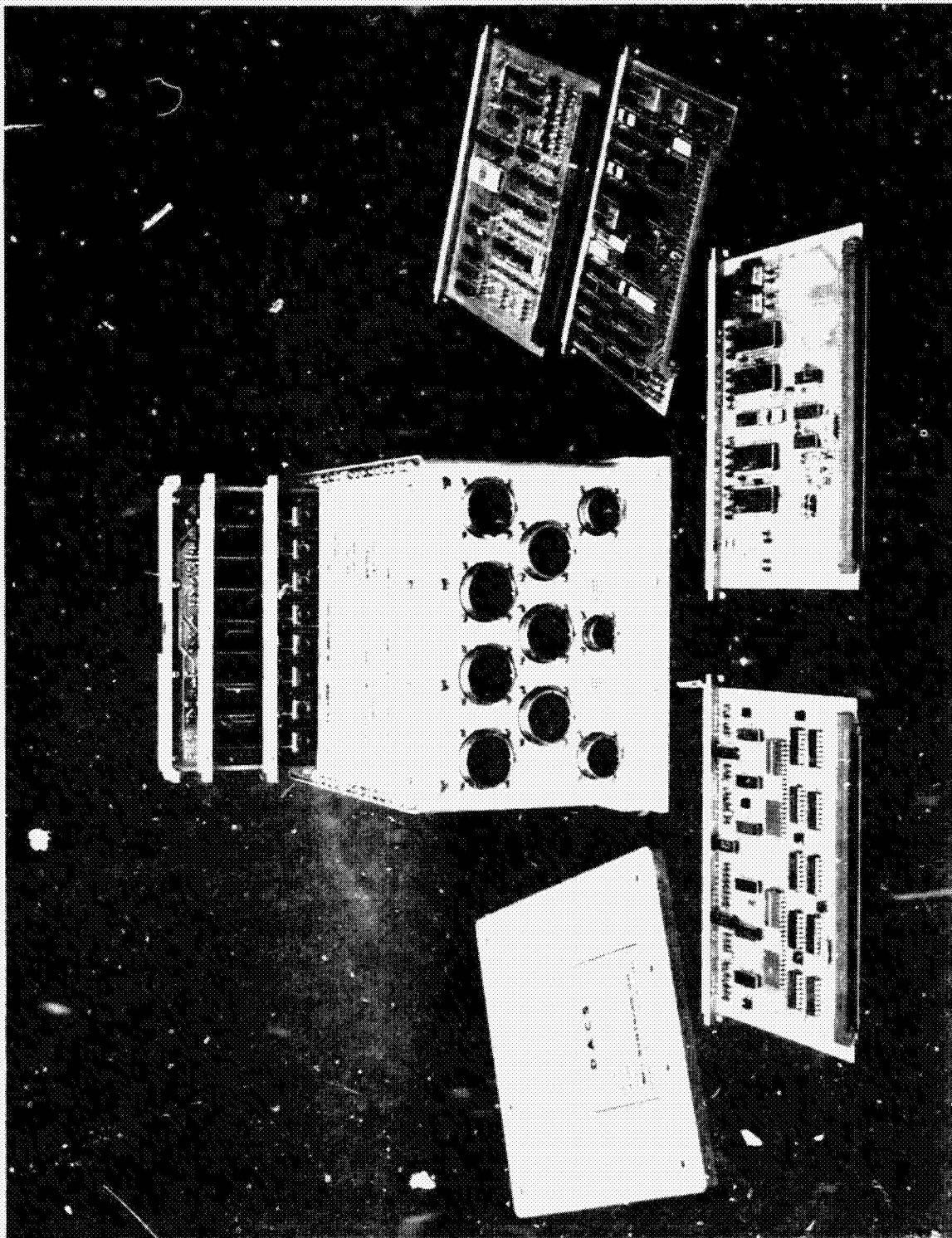


Figure III-13 DACS and Associated Circuit Boards

access memory (RAM) required is minimal (2K bytes) and is used to temporarily store data and operating parameters subject to change. The data acquisition portion of the DACS has the capability for multiplexing and/or digitizing about 70 analog signals and about 20 discretes. It interfaces directly with the controller data bus, including an analog-to-digital converter and multiplexer.

The position of the valves, and the valve control interfaces, allow the microprocessor to determine the status of any valve and to open or close the valve by issuing the appropriate instruction. The recorder interface allows the microprocessor to gather, format and record data. The recorder interface converts the parallel data from the microprocessor into a serial bit stream, and inserts parity and sync words as required. The sync words are stored in PROM and then placed into the bit stream as required. The microprocessor is capable of being restarted upon a loss of power or on command from the Aft Flight Deck.

The microprocessor controller operates all the valves except those needed only for safing functions. The latching valves require a 28-vdc pulse with a duration of less than 0.1 second. The pulse is generated in the microprocessor control logic. The valve drive circuit provides isolation between the signal and 28-vdc power grounds.

Since the CFME must be powered before Spacelab activation, the Orbiter essential bus is used. The use of the essential bus required consideration of the 300-watt limitation on this bus. The power allocation for experiments on this bus may be quite low. While on the essential bus, all unnecessary power drains have been eliminated. All valves, with the exception of the TVS valves and abort valves, are inoperable from the essential bus. The 300-watt heater is connected to the experiment bus rather than the essential bus.

Another design consideration was the in-rush current limitation on the Orbiter power buses. With 2 to 5-amp pulses required for the valve operations and with the 10-amp heater load, in-rush current limit circuitry and power line filtering were included. There are a considerable number of cables and wires interconnecting the DACS to its various interfaces. Figure III-14 shows the general configuration for the CFME cabling.

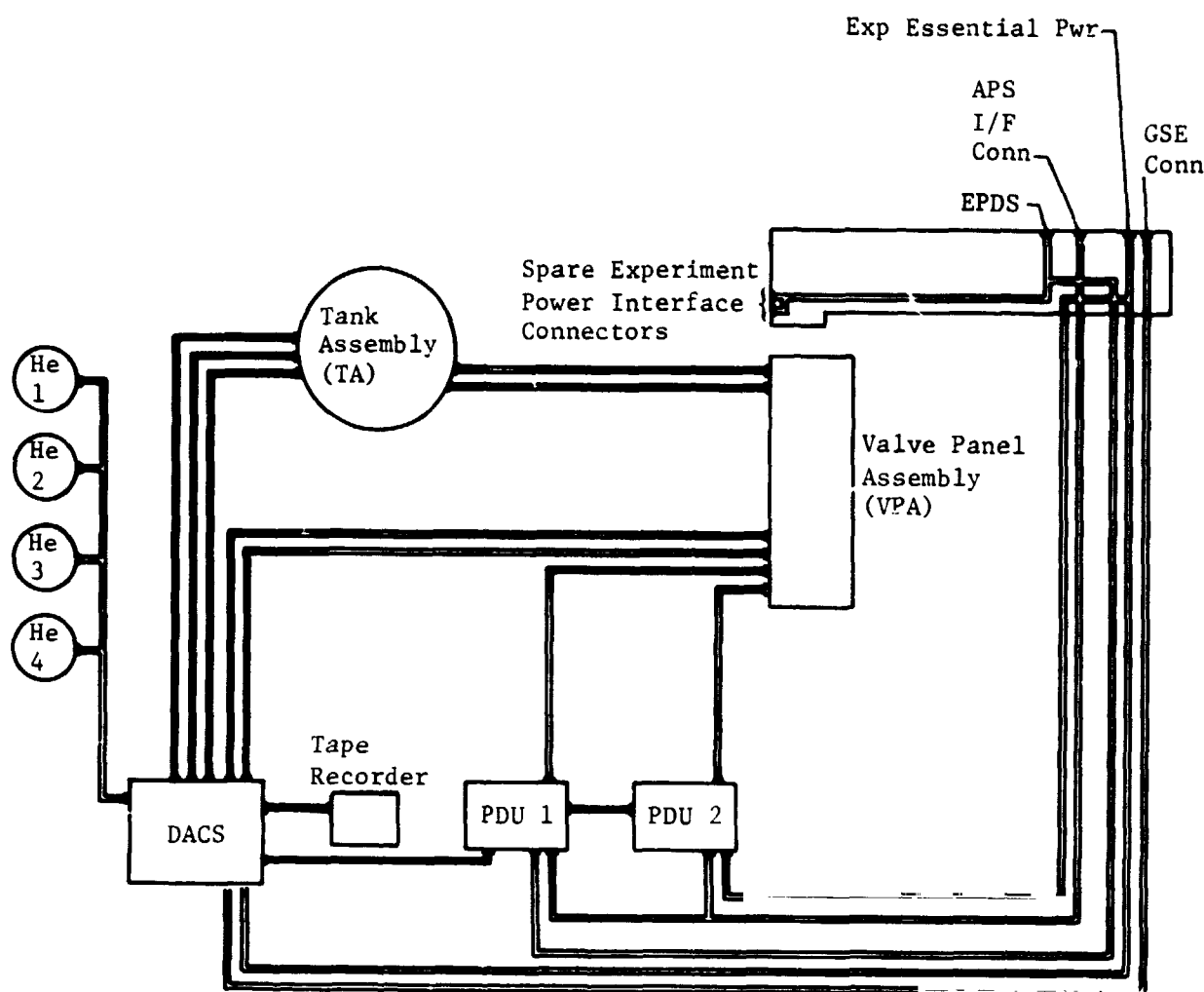


Figure III-14 CFME Wiring Diagram

8. Flow Systems. The details for the system components and line sizes are summarized below.

a. Outlet Line. This line carries the liquid hydrogen from the liquid acquisition device through the flow instrumentation to the Orbiter vent system or alternate user system. The line is 0.95-cm (0.375-in) diameter, leaving the liquid hydrogen storage tank through parallel lines containing separate isolation valves. These parallel lines tee together before exiting the tank assembly vacuum jacket. A density meter in the line outside the tank assembly vacuum jacket contains a 0.64-cm (0.25 in) u-tube with a minimal pressure drop

of  $20.7 \text{ kN/m}^2$  (3.0 psi) across the unit at the maximum flow rate of 81.6 kg/hr (180 lbm/hr). A heater wraps around the line (so it does not cause any flow constriction), and vaporizes the hydrogen prior to its entering the gas flowmeter, FE3, which is the primary means of flow measurement. The path through orifice R3C gives the minimum flowrate, and it is at this minimum flowrate condition that the heater/vaporizer is used. Gas flow is then measured with flowmeter FE3, and correlated with that measured by the liquid mass meter DM.

The lines through valves V3A and V3B are for higher flowrates. These lines bypass the gas flowmeter to avoid its relatively large pressure drop and prevent overranging of the meter. Orifice R3A controls the flowrate to 27.2 kg/hr (60 lbm/hr), and orifice R3B controls the flow to the maximum experiment and abort rate of 81.6 kg/hr (180 lbm/hr).

At the minimum normal flow rate of 1.5 kg/hr (3.3 lbm/hr) the pressure drop due to the liquid acquisition device, outlet valve, friction and losses due to bends, tees, etc., is negligible. A 300 W heater was selected to ensure vaporization of the liquid and increase the volumetric flowrate, which improves the resolution of the gas flowmeter. The heater raises the hydrogen from its saturation temperature of  $24.7^\circ\text{K}$  ( $44.5^\circ\text{R}$ ) to  $53^\circ\text{K}$  ( $95^\circ\text{R}$ ). Two-phase flow through the heater does not cause any appreciable pressure drop.

At the maximum experiment and abort flowrate of 81.6 kg/hr (180 lbm/hr), the pressure drop between the ullage and the heater is  $57 \text{ kN/m}^2$  (8.3 psi). With the hydrogen saturated at  $310 \text{ kN/m}^2$  (45 psia) and a tank pressure of  $379 \text{ kN/m}^2$  (55 psia), the hydrogen is still subcooled when it reaches the heater. The heater is left off at this higher flowrate since it can only vaporize a small portion of the liquid, and the vapor would only interfere with the metering of the flow by the orifice and valve.

b. Pressurization and Vent Lines. These lines provide for the flow of helium pressurant to the hydrogen storage tank and venting of the tank through either the ground servicing or T-0 vent lines. Regulation of the pressurization process is accomplished with two valves in series. The first valve is opened, admitting the high pressure helium to the volume between the valves. After closing the first valve, the second valve is opened, allowing blowdown

of the volume between valves into the tank. A redundant pair of valves is provided so that either leg can be used. By monitoring the valve position indicators, a leg with a valve failed-open or a valve that fails to open can be detected and the other leg can be used.

The valve cycling sequence includes the checking of the valve position, a period for stabilization and a comparison of the setpoint pressure with the tank pressure, all being performed by the experiment computer. A volume of 16 cm<sup>3</sup> (1.0 in<sup>3</sup>) between the two valves, and a valve cycle period of 0.27 seconds, allows about six cycles to maintain tank pressure at the minimum liquid outflow rate, while continuous cycling will meet the requirements for maximum experiment and abort outflow rates.

The pressurization orifices (R6 and R8), in combination with the filter and valves, limit the pressure of the tank during venting, should both control valves fail open. These orifices also limit the peak pressure during pressurization to avoid pressures near the operating point of the burst disks. The 6.4-cm (0.25-in) diameter lines are adequate for the pressurization plumbing.

There are two vent lines that interface with the Orbiter, each using 1.3-cm (0.5-in) diameter lines and valves. The ground servicing vent is used during tank loading and topping, and to reduce the tank pressure during ground hold (with the midbody umbilical still connected), should it become necessary. The airborne vent line is used from launch through completion of the mission for normal hydrogen vapor venting, emergency pressure relief and tank inerting. A horizontal vent line, which tees into the airborne vent, is used to reduce tank pressure during an abort landing when circumstances preclude tank draining. Valves V11 and V14 are tied into the airborne vent line and can either be commanded open or closed, or will automatically open if the tank pressure exceeds a designated limit. The burst disks permit pressure relief should either vent valve fail to open. The following conditions were evaluated in sizing the vent system components:

- o air leak into vacuum jacket,
- o hydrogen leak into vacuum jacket,
- o helium leak into vacuum jacket, and
- o venting of liquid hydrogen due to its orientation over the vent in low-g.



c. Thermodynamic Vent Lines. These lines consist of two heat exchangers that are attached to the vapor-cooled shield. The flow control valves are located outside the vacuum jacket. Temperature sensors are located inside the lines to obtain as accurate as possible vent gas data for thermal performance assessments. The hydrodynamic analysis (Chapter V) established that the only significant pressure drops in the thermodynamic vent lines are due to the Viscojets and the metering orifices. The lines are 0.48-cm (0.19-in) diameter.

d. Fill/Drain Line and Horizontal Drain Line. Lines and valves 1.3-cm (0.5-in) in diameter were selected for both of these lines. The fill/drain line is used for ground operations only, and interfaces with the Orbiter midbody umbilical. The horizontal drain line ties into the Orbiter T-0 umbilical airborne vent interface and is used only if the tank remains full following an RTLS abort landing.

9. Instrumentation/Data Collection. The experiment data consists of the measurements listed in Table III-1. The types, quantities and measurement periods are indicated in the table. The measurements used by the microprocessor as control functions are also indicated in the table. A complete summary of instrumentation, including ranges and accuracies is presented in Table III-2.

*Table III-1 Experiment Data Measurements*

Measurement (Qty)	Launch Pad & Ascent	On Orbit	Microprocessor Control Parameters
Temperature (54)	X	X	X
Pressure (11)	X	X	X
Flowrates (2)		X	
Fluid Density (1)		X	
Valve Positions (36)	X	X	X



<u>Measurement</u>	<u>Description (Number)</u>	<u>Range</u>	<u>Accuracy</u>
Temperature	Liquid Acquisition Device (6)	20-50 <sup>0</sup> K	$\pm 0.05^0\text{K}$
(54)	Pressure Vessel (6)	20-300 <sup>0</sup> K	
	Vapor Cooled Shield (10)	50-300 <sup>0</sup> K	
	Thermodynamic Vent System (6)	10-300 <sup>0</sup> K	
	Multi-Layer Insulation (2)	50-300 <sup>0</sup> K	
	Trunnion/Trunnion Support Tube (11)	100-400 <sup>0</sup> K	
	Tank Assembly Feed and Vent Lines (2)	20-300 <sup>0</sup> K	
	Vacuum Jacket (2)	100-400 <sup>0</sup> K	
	Helium Storage Tank (4)	100-400 <sup>0</sup> K	
	TVS Flowmeter Inlet (1)	100-350 <sup>0</sup> K	
	Hydrogen Vaporizer Outlet (1)	20-300 <sup>0</sup> K	
	DACS Internal Temperature (1)	200-400 <sup>0</sup> K	
	Hydrogen Outflow Line Temperature (1)	20-300 <sup>0</sup> K	
	Pressurization Tube Temperature (1)	20-300 <sup>0</sup> K	$\pm 0.05^0\text{K}$
Pressure	Hydrogen Tank Vertical (2)	0-689 kN/m <sup>2</sup>	$\pm 7 \text{ kN/m}^2$
(11)	Hydrogen Tank Horizontal (1)	0-689 kN/m <sup>2</sup>	$\pm 7 \text{ kN/m}^2$
	Helium Storage Sphere (2)	0-25000 kN/m <sup>2</sup>	$\pm 250 \text{ kN/m}^2$
	Tank Outlet (1)	0-689 kN/m <sup>2</sup>	$\pm 7 \text{ kN/m}^2$
	Hydrogen Vaporizer Outlet (1)	0-689 kN/m <sup>2</sup>	$\pm 7 \text{ kN/m}^2$
	TVS System 1 (1)	0-689 kN/m <sup>2</sup>	$\pm 7 \text{ kN/m}^2$
	TVS System 2 (1)	0-689 kN/m <sup>2</sup>	$\pm 7 \text{ kN/m}^2$
	Vacuum Jacket (1)	0-35 kN/m <sup>2</sup>	$\pm .35 \text{ kN/m}^2$
	TVS Flowmeter Inlet (1)	0-689 kN/m <sup>2</sup>	$\pm 7 \text{ kN/m}^2$

**BOLDOUT FRAME**

	<u>Accuracy</u>	<u>Sensor Type</u>	<u>Signal Conditioning</u>	<u>Data Readout or Storage</u>
	$\pm 0.05^{\circ}\text{K}$	Variable Resistance	Bridge Completion Amplifier	Display/Tape
	$\pm 0.05^{\circ}\text{K}$	Variable Resistance	Bridge Completion Amplifier	Display/Tape
$\text{N/m}^2$	$\pm 7 \text{ kN/m}^2$	Strain Gage	Amplifier	Display/Tape
$\text{N/m}^2$	$\pm 7 \text{ kN/m}^2$	(0-5 VDC)		
$\text{kN/m}^2$	$\pm 250 \text{ kN/m}^2$			
$\text{N/m}^2$	$\pm 7 \text{ kN/m}^2$			
$\text{N/m}^2$	$\pm 7 \text{ kN/m}^2$			
$\text{N/m}^2$	$\pm 7 \text{ kN/m}^2$			
$\text{N/m}^2$	$\pm 7 \text{ kN/m}^2$			
$\text{m}^2$	$\pm .35 \text{ kN/m}^2$			
$\text{N/m}^2$	$\pm 7 \text{ kN/m}^2$	Strain Gage (0-5 VDC)	Amplifier	Display/Tape

EXCLUDED FRAME 2

Table III-2 Instrumentation Sensor Description

<u>Measurement</u>	<u>Description (Number)</u>	<u>Range</u>	<u>Accur</u>
Flow Rate	LH <sub>2</sub> Outflow Flowrate (1)	0-3.4 kg/hr	<u>±</u> 0.
(2)	TVS Flowrate (1)	0-0.2 kg/hr	<u>±</u> 0.
Density	LH <sub>2</sub> Outflow Density (1)	0-80 kg/m <sup>3</sup>	<u>±</u> 0.04
(1)			
Liquid Level	LH <sub>2</sub> Point Level Sensor (2)	Covered/	<u>±</u> 0.
(2)		Uncovered	
Voltage	LH <sub>2</sub> Vaporizer (1)	0-28 Volts	<u>±</u> 1
(1)			
Current	LH <sub>2</sub> Vaporizer (1)	0-20 Amps	<u>±</u> 1
(1)			
Position	Experiment Shutoff Valves (18)	OVDC/28VDC	- - -
(18)			

FOLDOUT FRAME

FOLDOUT FRAME

Table III-2 Instrumentation Sensor Description (Conc.)

	<u>Accuracy</u>	<u>Sensor Type</u>	<u>Signal Conditioning</u>	<u>Data Readout or Storage</u>
g/hr	<u>±</u> 0.02 kg/hr	Drag Body	Level Shifted	Display/Tape
g/hr	<u>±</u> 0.02 kg/hr	Drag Body	Level Shifted	Display/Tape
/m <sup>3</sup>	<u>±</u> 0.04 kg/m <sup>3</sup>	Tube Motion	Level Shifted	Display/Tape
ed	<u>±</u> 0.076 cm	Hot Wire	None	Display/Tape
lts	<u>±</u> 1 volt	Voltmeter	Voltage Divider	Display/Tape
mps	<u>±</u> 1 amp	Shunt	None	Display/Tape
VDC	- - - -	Switch	None	Display/Tape

FOLDOUT FRAME

2

All experiment data while on the pad is available through the umbilical on the EGSE serial interface line. The tape recorder stores data during the period from liftoff until the experiment is terminated at the end of the mission. The tape recorder selected for the experiment is the Lockheed Electronics Mark V, Type 4200, pictured in Figure III-15. Although this tape recorder provides higher density data recording than is required for the CFME, it is a suitable recorder and the most economical choice. Some of the pertinent tape recorder specifications are given in Table III-3.

*Table III-3 Tape Recorder Specifications*

Configuration	Coaxial Reel to Reel
Size	23.6 x 13.7 x 13.5 cm (LxWxH) (9.3 x 5.4 x 5.3 in)
Weight	3.0 kg (6.5 lbm)
Power Consumption	4 W maximum
Tape Speed	2.5 cm/sec (1.0 in/sec) minimum
Tape Capacity	140 m (450 ft) high-temperature tape
Record Time	4 hr (4 track)
Packaging	Hermetically Sealed

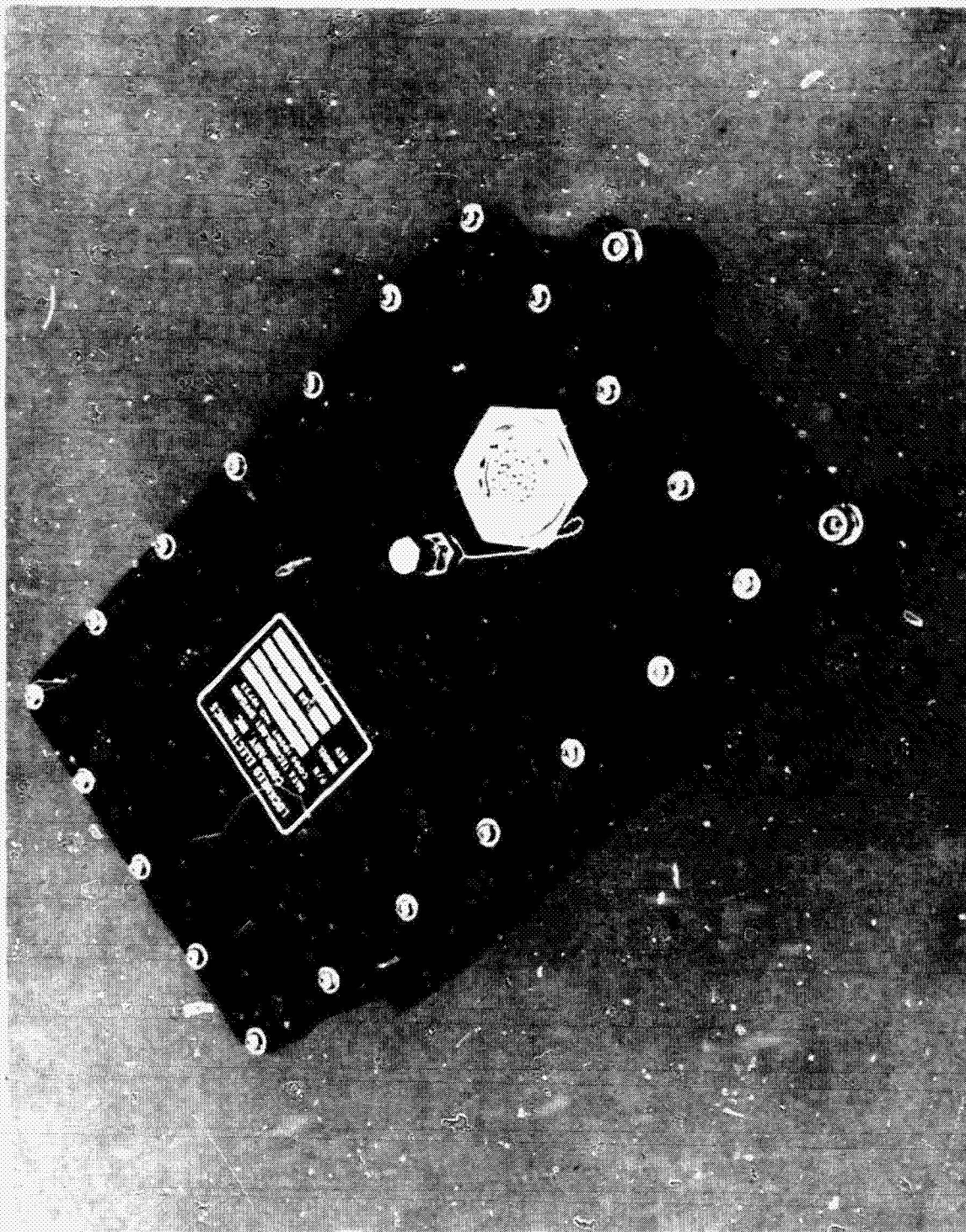


Figure III-15. CFME Tape Recorder

The tape recorder requires 12 vdc power, which is supplied from the DACS power supply. The recorder is controlled by the DACS, and has four tracks for 7.2 million bytes of recording capability, adequate for data recording. The recorder has no self-contained reproduce head or electronics. Rather, a reproduce unit (Lockheed Electronics GRU4200) is supplied as GSE and is used for data retrieval when the Orbiter returns to earth.

10. Weight Summary. A summary of the weights of the flight hardware and the commodities in the tanks at liftoff is presented in Table III-4. The hardware weight is broken into two pieces, the hydrogen tank assembly and the experiment supporting systems. It should be noted that these weights are consistent with a very conservative approach to the structural design because of the experimental nature of the CFME and the use of hydrogen within the shuttle cargo bay. The design requirements in Chapter II and the structural margins of safety for the detailed design listed at the end of Chapter V, indicate the degree of safety built into the design.

In addition to the conservative design factors, the dynamic environment and structural loads for payloads mounted on the Spacelab pallet are quite severe and this results in added structure and weight. For example, the experiment pallet structure, which interfaces at the Spacelab pallet hardpoints, weighs 124.1 kg (273.5 lb). This heavy I-beam configuration was dictated by the SPAH SLP/2104 requirement that the payload package mounted to the hardpoints must have a fundamental frequencies above 35 Hz and must withstand significant specified deflections between the hardpoints. However, even with these structural considerations, the total loaded CFME weight is not a problem since the weight is not excessive for the portion (percent volume and envelope) of the pallet which it occupies.

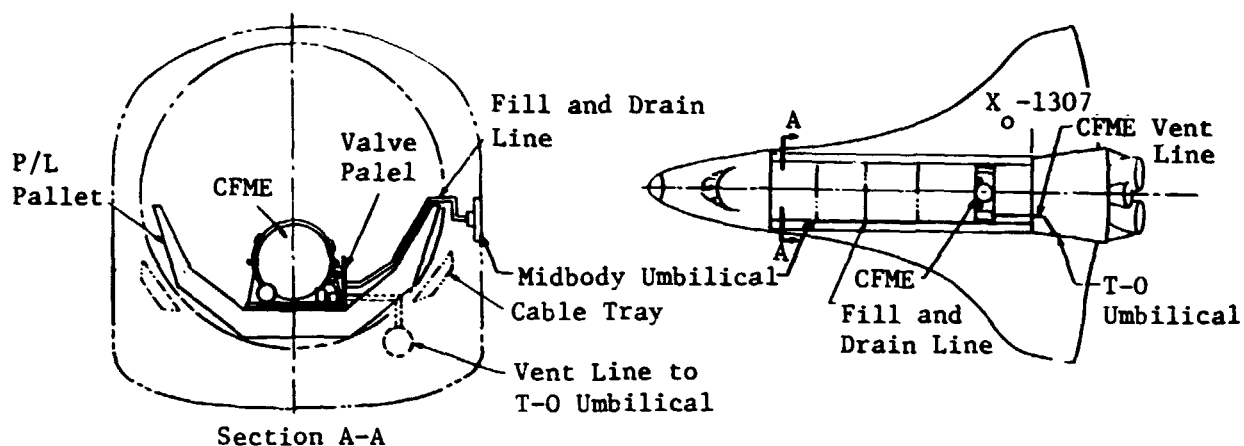
Table III-4 Experiment Weight Summary

Item	Weight	
	kg	(lb)
<u>TANK SYSTEM</u>		
LH2 Storage Tank Assy	33.8	(74.4)
Thermal Control System	28.4	(62.7)
LH2 Tank Supports and Outflow Valves	8.4	(18.4)
Vacuum Jacket	39.7	(87.6)
Girth Ring	<u>23.4</u>	<u>(51.6)</u>
Total Tank System	133.7	(294.7)
<u>SUPPORT SYSTEMS</u>		
GHE Pressurant Tanks and Structure	44.5	(98.2)
Electronics and Cables	37.0	(81.5)
Pallet Structure	124.1	(273.5)
Service Line Interface Panel and Structure	<u>64.3</u>	<u>(141.8)</u>
Total Support Systems	269.9	(595.0)
Total Dry CFME	403.6	(889.7)
<u>COMMODITIES</u>		
LH2	42.5	(93.6)
GHE	<u>2.9</u>	<u>( 6.4)</u>
Total Commodities	45.4	(100.0)
Total Loaded CFME	449.0	(989.7)



## B. Orbiter Interfaces.

When the CFME is installed in the Orbiter cargo bay, it interfaces both mechanically and electrically with supporting Orbiter systems, as illustrated in Figure III-16. Structural hardpoints attach the experiment to the Spacelab pallet. Dedicated interfaces connect the CFME to experiment-specific GSE for ground checkout and servicing.

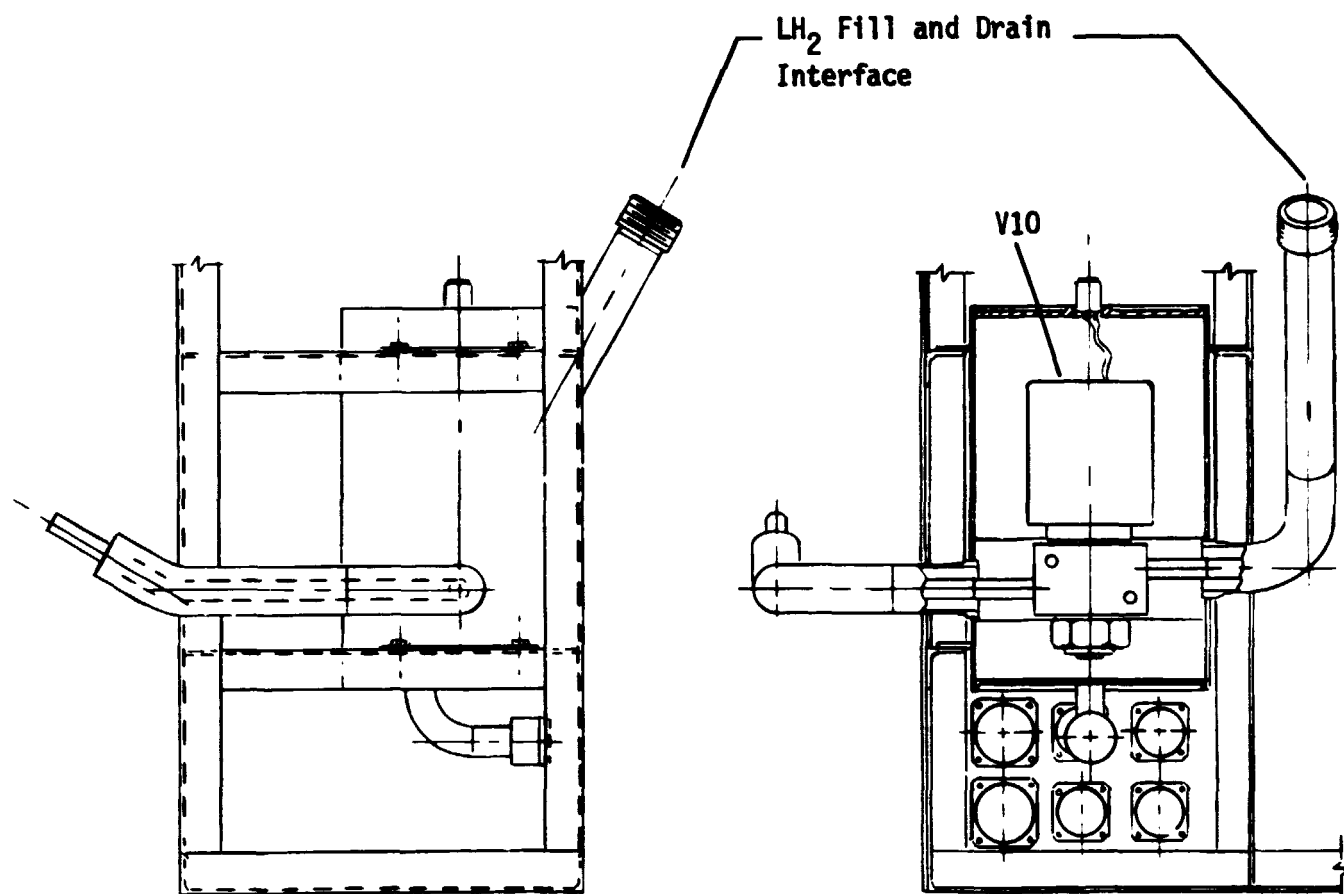


*Figure III-16 CFME Orbiter Interfaces*

1. Orbiter Fluid Mechanical Interfaces. The mechanical interfaces between the CFME and the Orbiter are the fill/drain line, the ground servicing vent line and the T-O umbilical vent line.

LH2 Fill/Drain Line. A female 1/2-inch vacuum-jacketed Cryolab threaded bayonet fitting, as shown in Figure III-17, is provided at the CFME valve panel to mate with the Orbiter plumbing from the midbody umbilical panel fill and drain disconnect.

Ground Servicing Vent. A 1/2-inch tube stub, as shown in Figure III-18, is provided at the CFME valve panel to mate with the Orbiter plumbing from the midbody umbilical panel ground servicing vent disconnect.



*Figure III-17 LH<sub>2</sub> Fill/Drain Valve Panel Interface*

T-0 Umbilical Vent. A 1/2-inch tube stub, as shown in Figure III-18, is provided at the CFME valve panel to mate with the Orbiter plumbing from the T-0 umbilical vent disconnect.

These three interfaces will be subjected to helium gas pressurizations for experiment inerting and leak checks at pressures up to 413 kN/m<sup>2</sup> (60 psia). Reactant purging using gaseous hydrogen at the same pressures may also be accomplished. Liquid hydrogen servicing and experiment operations will

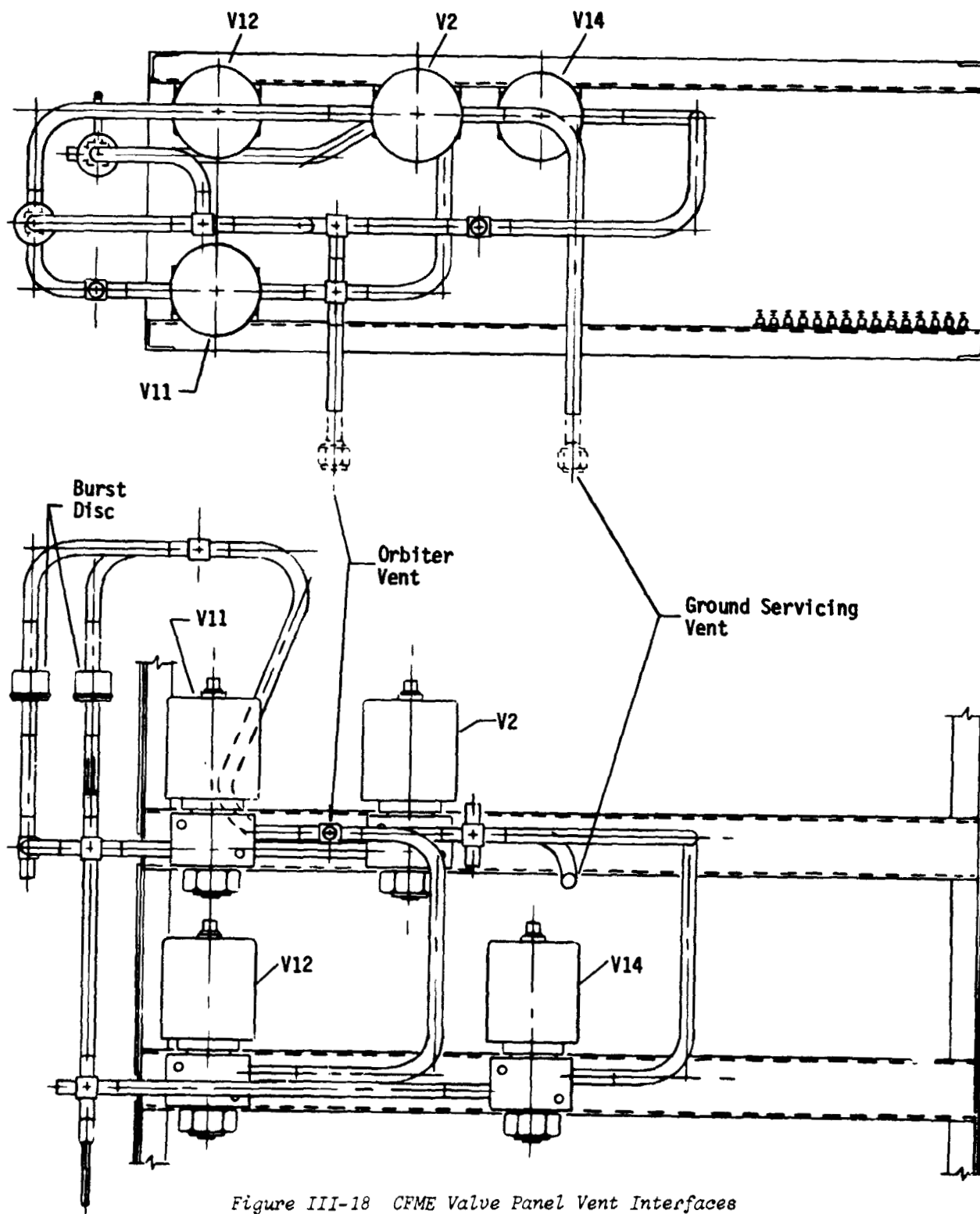


Figure III-18 CFME Valve Panel Vent Interfaces

introduce LH2 at all three interfaces at a maximum pressure of  $413 \text{ kN/m}^2$  (60 psia). Temperature ranges to which these fluid connections are exposed are as follows:

Ground Servicing  $-253^{\circ}$  to  $38^{\circ}\text{C}$  ( $-423^{\circ}$  to  $100^{\circ}\text{F}$ )

Flight Environment  $-253^{\circ}$  to  $60^{\circ}\text{C}$  ( $-423^{\circ}$  to  $140^{\circ}\text{F}$ )

Because of the multimission usage of the CFME, one desirable change that should be considered during the experiment integration effort is to replace the two 1/2-inch tube stub interfaces defined above with 1/2-inch male Dynatube fittings. This will provide a better "reusable" interface for connecting and disconnecting the lines for each flight.

## 2. Orbiter Electrical Interfaces.

T-0 Umbilical EGSE. An eight signal (16 pin) connector is provided on the DACS to connect with a T-0 umbilical cable from the EGSE for ground control and monitoring prior to launch.

28VDC Orbiter Bus Power. Two Orbiter bus power cables interface with the CFME power distribution units (PDU). One provides power from the essential bus to operate the DACS tape recorder and TVS valves, while the other provides power from the Spacelab experiment bus. A summary of the experiment power requirements is presented in Table III-5.

OCP on Aft Flight Deck. The CFME Operation Control Panel on the Aft Flight Deck uses standard switches and talkbacks on dedicated experiment panels, and connects to the DACS via Orbiter cabling.

28VDC Abort Landing Ground Power. A PDU cable interfaces with the T-0 umbilical provides 28 VDC power to the CFME in an abort landing situation if fuel cell power is shutdown.

3. Orbiter/Spacelab Pallet Structural Connections. Pickup points are provided on the CFME pallet structure for attaching horizontal and vertical lifting slings which are required for CFME processing, including installation on the Spacelab pallet. Mounting of the CFME to the Spacelab pallet is

Table III-5 Experiment Power Requirements

	Standby Power (Watts)	Average Power (Watts)		Peak Power (Watts)
		Low Flow (3 : 1b/hr)	High Flow (60 or 180 1b/hr)	
DACS	40	40	40	40
Tape Recorder	0	0	0	4
Electronics Heater	50	50	50	50
Outflow Heater		400	0	400
Vent-Sol. Valves		6	6	60*
Press-Sol. Valves		6	6	60*
Instrumentation, OCP Indicators	28	28	28	28
Total	118	532	132	582

\* Only one valve operating at a time, drawing peak power

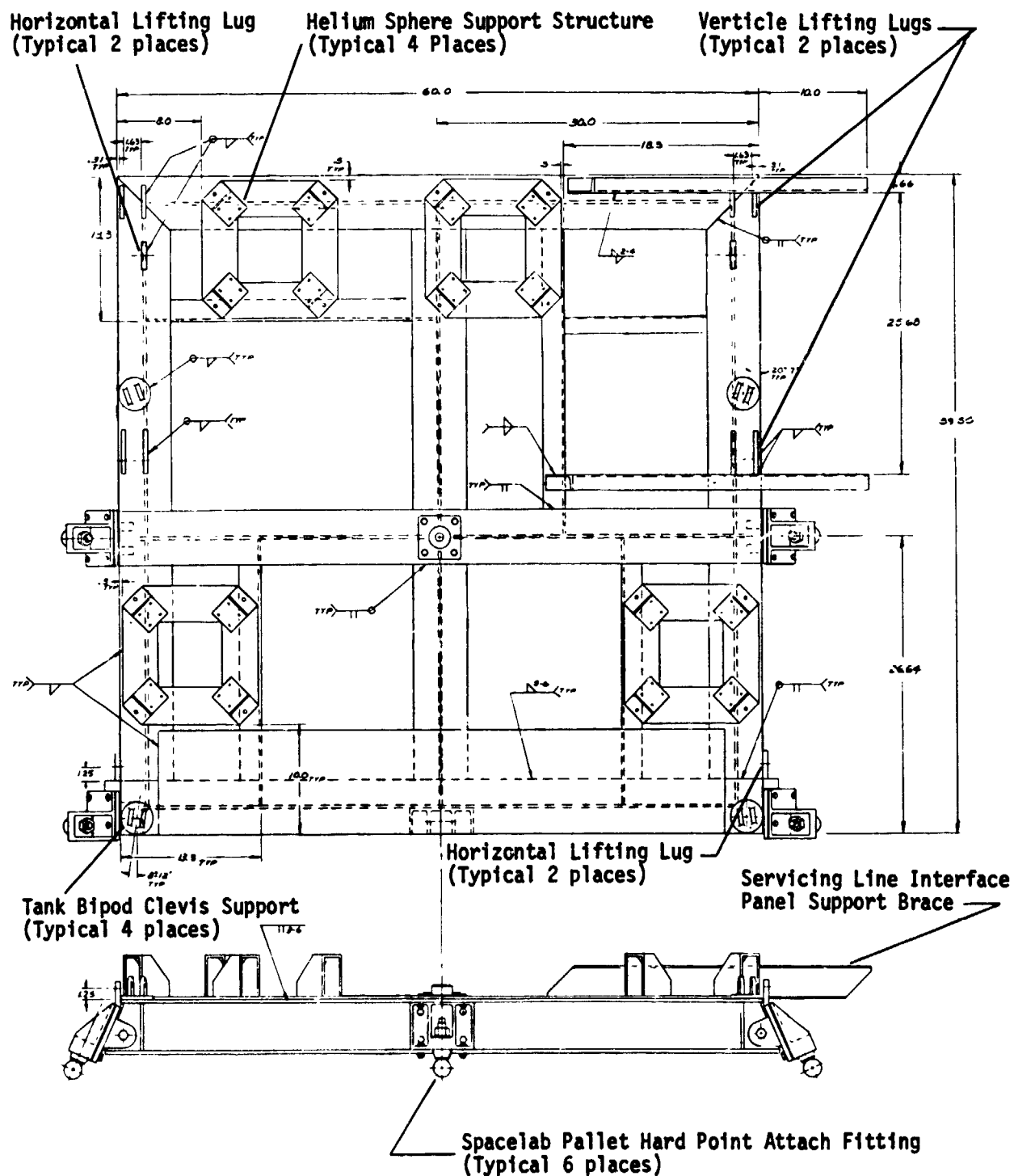


Figure III-19 CFME/Spacelab Pallet Mounting

accomplished through six hardpoint connections (threaded shanks), as shown in Figure III-19. The CFME is secured to the pallet at the hardpoint location with washers and nuts which are lockwired after installation.

4. Operation Control Panel. The talkbacks and switches on the OCP located on the Aft Flight Deck for Mission Specialist monitoring and control of the CFME are shown schematically in Figure III-20. The alert talkbacks provide an indication to the flight crew that the experiment has automatically transferred from normal operations to an abort and inerting mode. Initiation of an abort may also be made by various manual switch inputs through the OCP. A description of the OCP functions is presented in the following paragraphs.

Mission Sequences and Sequence Indication. This portion of the OCP interfaces with the experiment clock, which resides in the DACS, and consists of three talkbacks and a sequencer switch. The experiment timeline for each flight will be divided into seven time periods which will be displayed in a binary fashion on the sequence indicator talkbacks. As the experiment progresses through a normal mission, the talkbacks will cycle, giving the Mission Specialist a relative indication of proper experiment elapsed time vs. mission elapsed time. They also give an indication that the experiment is powered up and properly operating.

An example of how a typical CFME mission timeline can be divided into seven periods is as follows:

- 1 - 40-hour self-pressurization
- 2 - 40-hour stabilization at  $310 \text{ kN/m}^2$  (45 psia)
- 3 - 1.2-hour outflow at  $310 \text{ kN/m}^2$  (45 psia)
- 4 - Storage and pressurization to  $379 \text{ kN/m}^2$  (55 psia) and a 40 minute expulsion
- 5 - 33-hour storage at  $379 \text{ kN/m}^2$  (55 psia)
- 6 - Blowdown and 8-hour expulsion at  $310 \text{ kN/m}^2$  (45 psia)
- 7 - Pressurization, depletion and inerting

If the DACS loses power, but is repowered within 60 minutes, then the following procedure is followed to assure that the programmed mission in the DACS software is transferred to the proper location. Normally, as power

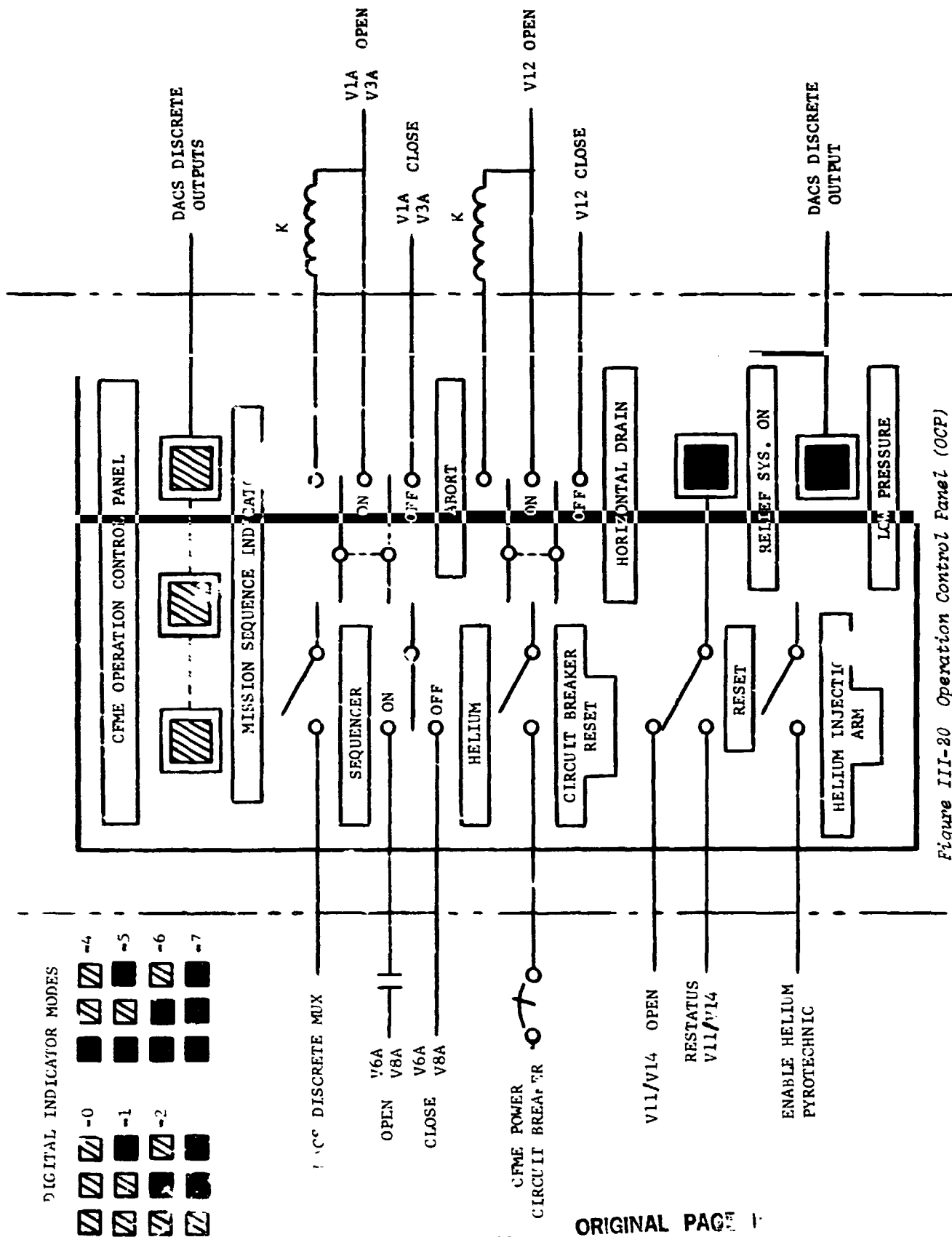


Figure III-20 Operation Control Panel (OCP)



returns to the DACS, the software will reset the experiment clock to zero and start the mission timeline all over again. (The circuit breaker on the CFME OCP may need to be reset following the power-down). The DACS will send a signal to the Mission Sequence Indicator, indicating that it has been powered-up. The Mission Specialist then restarts and transfers the experiment to the proper mission mode using the Mission Sequencer on the OCP. Mission Sequence Instructions supplied with the OCP will be used to establish the operating procedure for the Mission Sequencer and Mission Sequence Indicator. Basically, a table of mission elapsed time and experiment timeline modes will be used. The experiment timeline will have been divided into the seven time periods as defined above and, based upon the mission elapsed time, the Mission Specialist will sequence the software to the beginning of the next experiment time period.

Abort Switch. Actuation of this switch supplies power to valves V1A and V3A and cycles them to the open position. Draining of the LH2 tank through the T-0 vent is initiated. The DACS is also transferred into the abort mode (Sequence 7) and automatically commands inerting of the LH2 tank.

Helium Backup Switch. Actuation of this switch supplies power to valves V6A and V8A and cycles them to the open position. This permits all of the helium in the three non-isolated spheres to be injected into the tank. Orifice R8 is sized to control the flowrate to a maximum equivalent to that required for expelling liquid at 81.6 kg/hr (180 lb/hr). This switch is interlocked with the Abort or Horizontal Drain switches, and will not operate unless a vented flow path is provided for gas outflow. This precludes inadvertent relief valve operation and possible burst disc rupture which would occur without the tank outflow or drain being open.

Horizontal Drain Switch. This switch opens valve V12 and signals the DACS to execute the preprogrammed horizontal drain sequence. The DACS will regulate the helium pressurization subsystem to accomplish the draining at a rate of 81.6 kg/hr (180 lb/hr).

System Relieving Pressure Talkback and Reset Switch. An "on" indication from this talkback indicates that either valve V11 or valve V14 has opened due to a LH2 tank pressure exceeding  $413 \text{ kN/m}^2$  (60 psia). The reset switch restatues the valve position. If either is open, the talkback will remain on.

LH2 Tank Low Pressure Talkback. The tank pressure is checked each time the DACS cycles through the instrumentation signals. If tank pressure is below the initial loaded pressure of  $103 \text{ kN/m}^2$  (15 psia) then the low pressure talkback will be illuminated, indicating a leak or a burst disc rupture.

Circuit Breaker Reset Switch. If the CFME circuit breaker trips and the CFME loses power, the power circuit breaker can be reset from this switch on the OCP.

Helium Injection Arm. This switch arms the pyrotechnic device in the helium injection system. The command will be sent at the proper time in the mission sequence to activate the DACS software.

Talkback Indicators. Valves V11 and V14 "open", and LH2 tank "low pressure" talkbacks indicate system failures. The following talkback conventions define system status; graybar indicates that the system is normal and red stripe indicates a system failure.

## 5. Mechanical GSE Interfaces.

Helium Servicing. At the CFME valve panel, a 1/4-inch capped AN port interfaces with a facility (O and C Building) high pressure helium supply line for servicing the GHe tanks. The port at the valve panel is shown on the drawing in Figure III-21.

Tank Vacuum Jacket. A capped Cryolab high vacuum pumpout port is provided for checking, maintaining, and re-establishing the LH2 tank assembly vacuum. The port is located in the VJ girth ring, as seen in Figure III-22.

Flow Line Vacuum Jacket. A capped Cryolab vacuum pumpout port is provided for each section of vacuum-jacketed line to check and maintain vacuum in the jackets. A representative pumpout port installation is shown in Figure III-23.

6. Electrical GSE Interfaces. A playback interface for post-mission experiment data retrieval is provided on the tape recorder. This interface connects to a ground reproduce unit for data recovery.

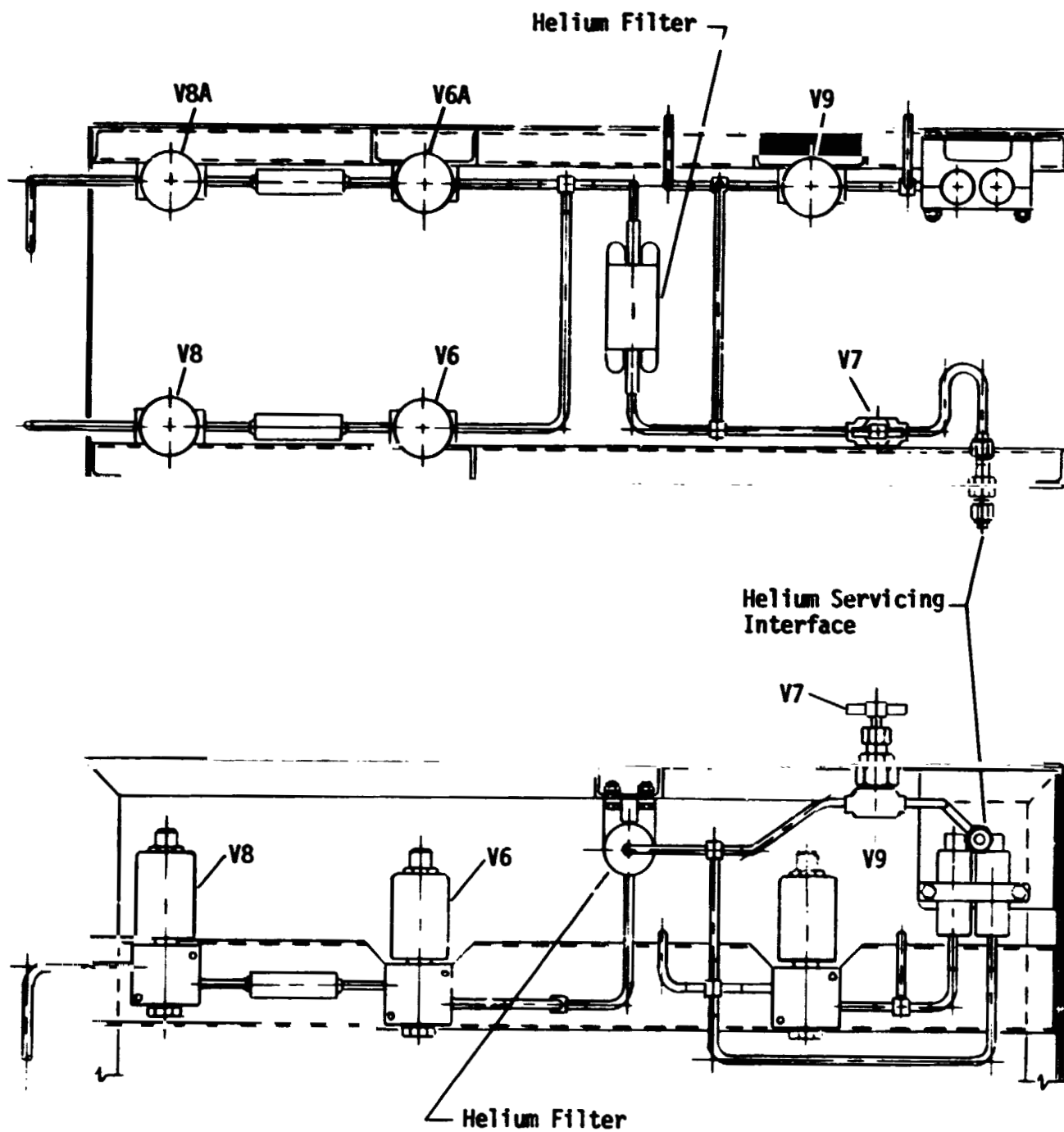


Figure III-21 Helium Servicing Interface

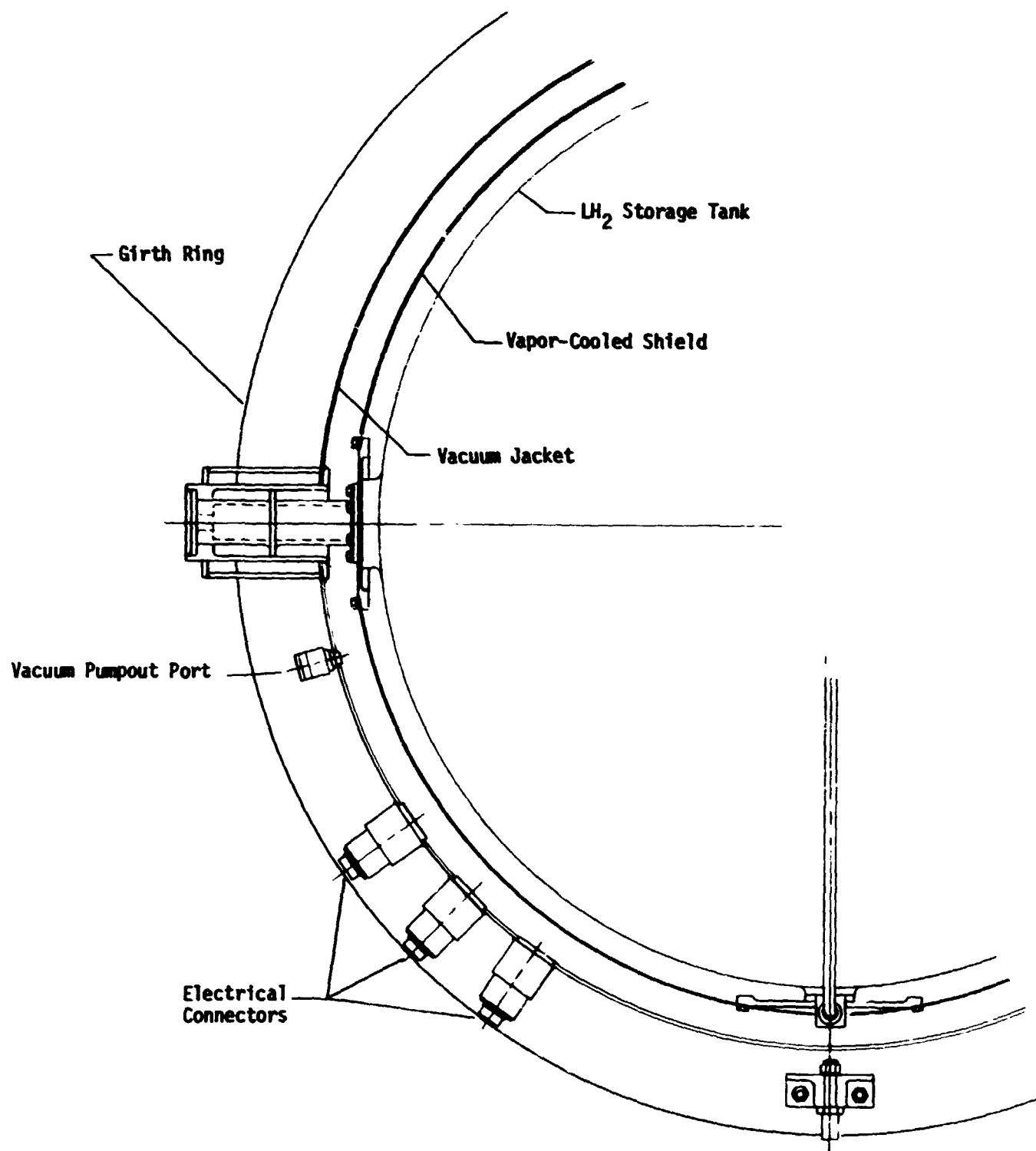


Figure III-22 Tank Vacuum Jacket Pumpout Port

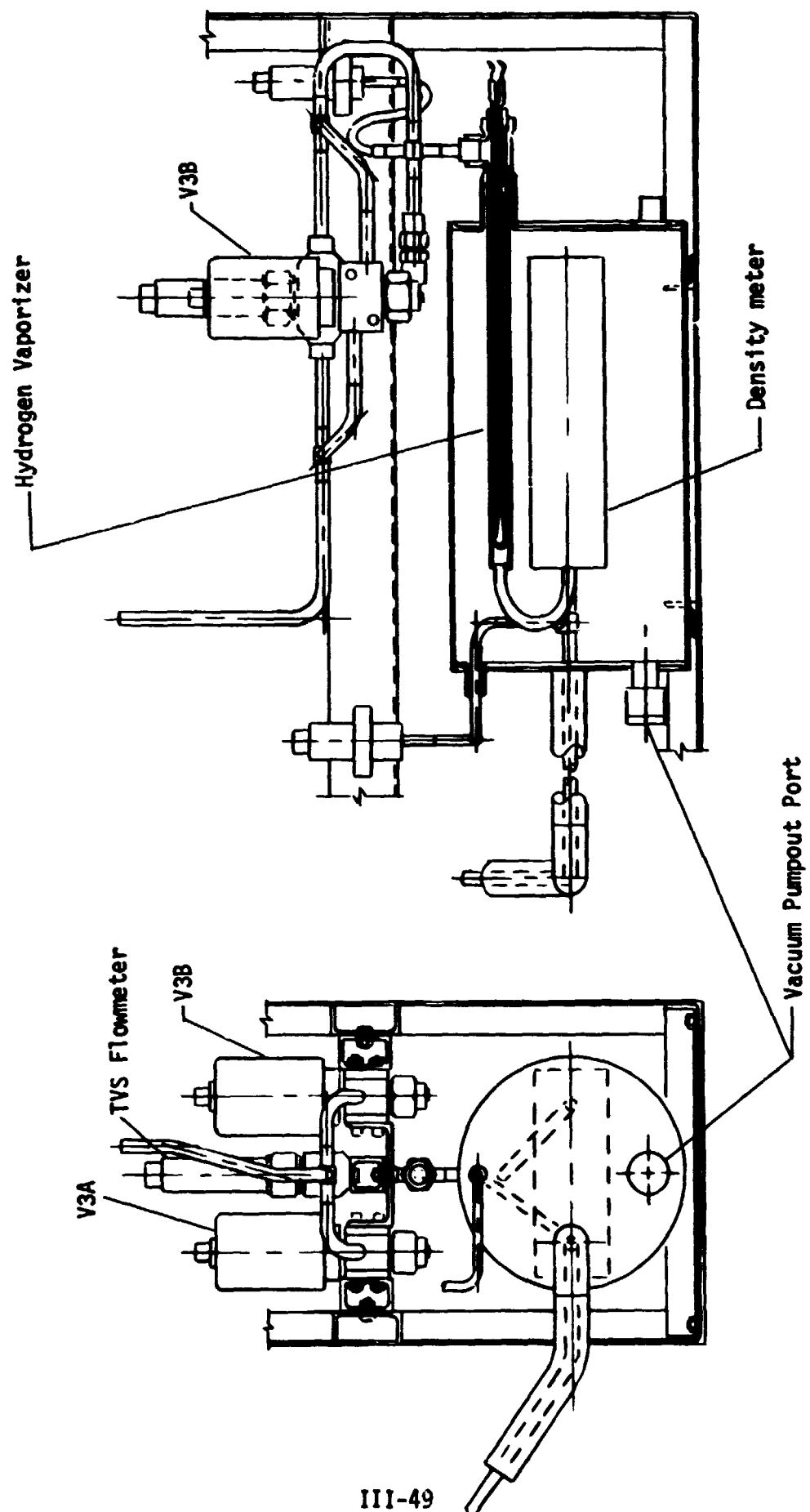


Figure III-23 Flow Line Vacuum Jack-pump Port

### C. Ground Support Equipment Description.

Ground Support Equipment (GSE) required to support the CFME program is grouped into four categories, as follows: 1) Equipment and test tools required to support pre-delivery ground testing of the CFME, 2) GSE required to accomplish CFME integration onto the Spacelab pallet and into the Orbiter at KSC, 3) KSC supplied GSE for CFME operations, and 4) Electrical GSE, which consists of the hardware necessary to test, operate, status and retrieve data from the CFME.

The specific items of GSE in each of these categories are discussed in this Section.

1. GSE and Test Tools for Ground Test Program. A GSE test tooling matrix is shown in Table III-6. The matrix delineates which GSE is used for the various tests and operating modes, and illustrates the involvement of the various fixtures and servicing equipment discussed in the following paragraphs.

a. Vibration Test Fixtures. The vibration test fixtures are configured as shown in Figures III-24 and III-25 to support the CFME in a vertical (Z) axis and lateral (Y) axis position for all vibration testing. In both cases the CFME is positioned in the horizontal attitude. Loading and offloading of liquid hydrogen in the horizontal position is required during the course of this test.

b. Thermal Vacuum Test Support Hardware. The thermal vacuum test setup is shown in Figure III-26, and consists of a test chamber and vacuum system, vertical lifting device for mounting the CFME in the chamber, radiant heater panels, a LN<sub>2</sub> cold-wall plate, and a LH<sub>2</sub> fill and drain system.

The CFME is installed in the thermal vacuum chamber using the vertical lifting device. The following interface connections are then made: 1) LH<sub>2</sub> fill and drain, 2) LH<sub>2</sub> ground vent, 3) LH<sub>2</sub> T-0 vent, 4) GHe pressurization, 5) electrical control cables, and 6) instrumentation cables.

The desired heat flux to the experiment is provided by radiant heat lamps and the cold wall in a pre-established vacuum of 0.01 micron ( $1 \times 10^{-5}$  torr).

	Tests																		
	Pressure Vessel Burst	LAD Static Test	LAD Modal Survey	Vacuum Integrity Test	System Proof Pressure	Internal and External Leakage	Relief System Verification	LH <sub>2</sub> Fill and Drain	LH <sub>2</sub> Tank Topping	Nonvented Hold Capability	Thermodynamic Vent System Operation	TVS Hold Capability	Horizontal Attitude Drain	Outflow and LAD Operation	Normal Gravity Abort Drain	High and Voltage	Vibration	Thermal Vacuum	Electromagnetic Compatibility
Ground Support Equipment/Test Tools					X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Transportation Skid & Protective Cover					X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Lifting & Handling Fixtures	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Vibration Test Fixture													X				X		
Thermal Vacuum Chamber																		X	
Electromagnetic Compatibility Setup																			X
Vacuum Pumps				X														X	
Pressurization Systems	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
LH <sub>2</sub> Fill & Drain System								X	X	X	X	X	X	X	X		X	X	
LH <sub>2</sub> Storage Dewar								X	X	X	X	X	X	X	X		X	X	
EGSE Monitor & Control Console					X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Helium Leak Detector						X													
Weigh Scale								X	X	X	X	X	X	X	X				
Shaker Table		X												X	X				
Static Test Fixture			X																
Electrical Test Equipment	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Table III-6 Ground Support Equipment/Test Tooling Matrix

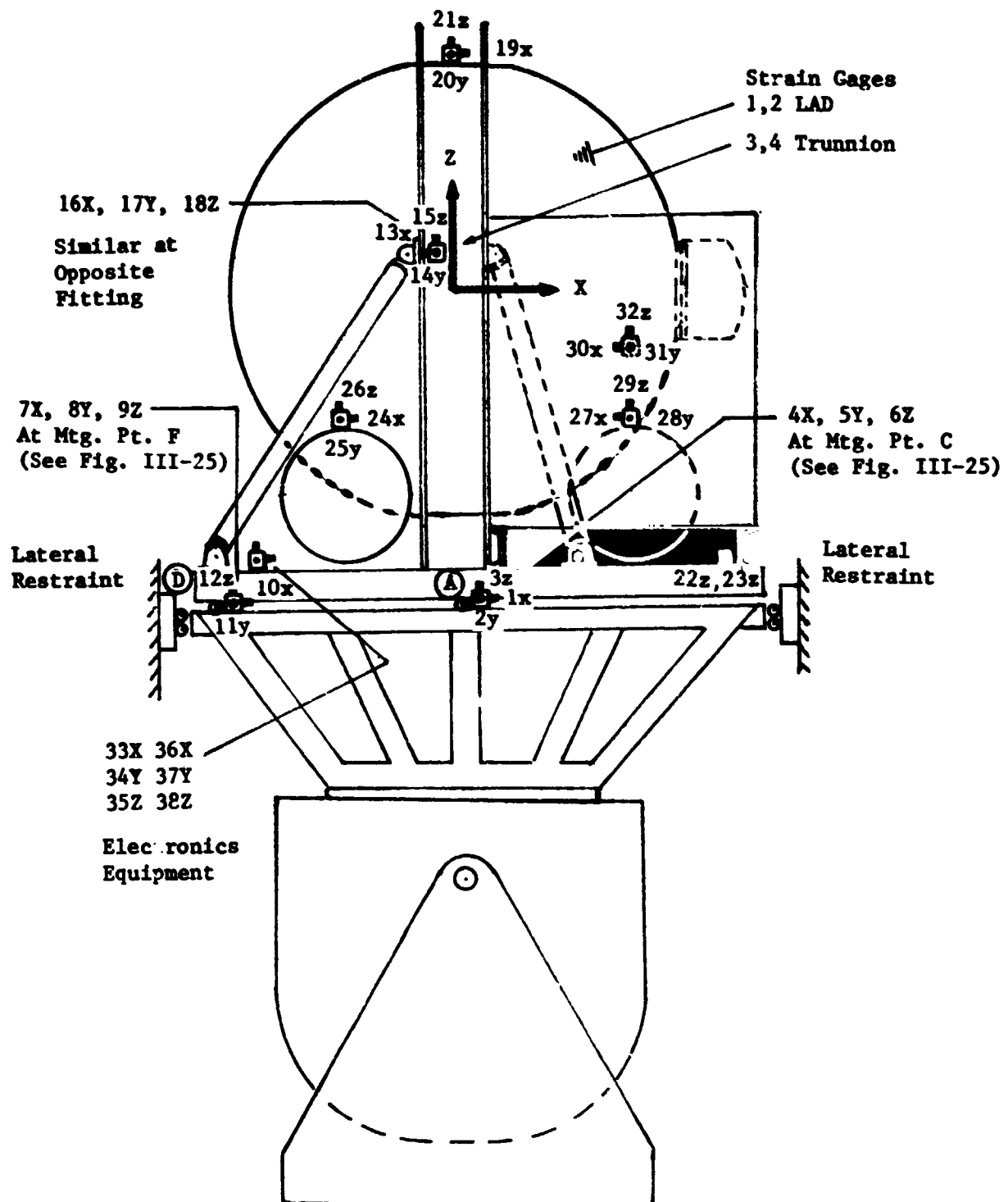


Figure III-24 Vertical (Z) Axis Vibration Test Fixture Configuration



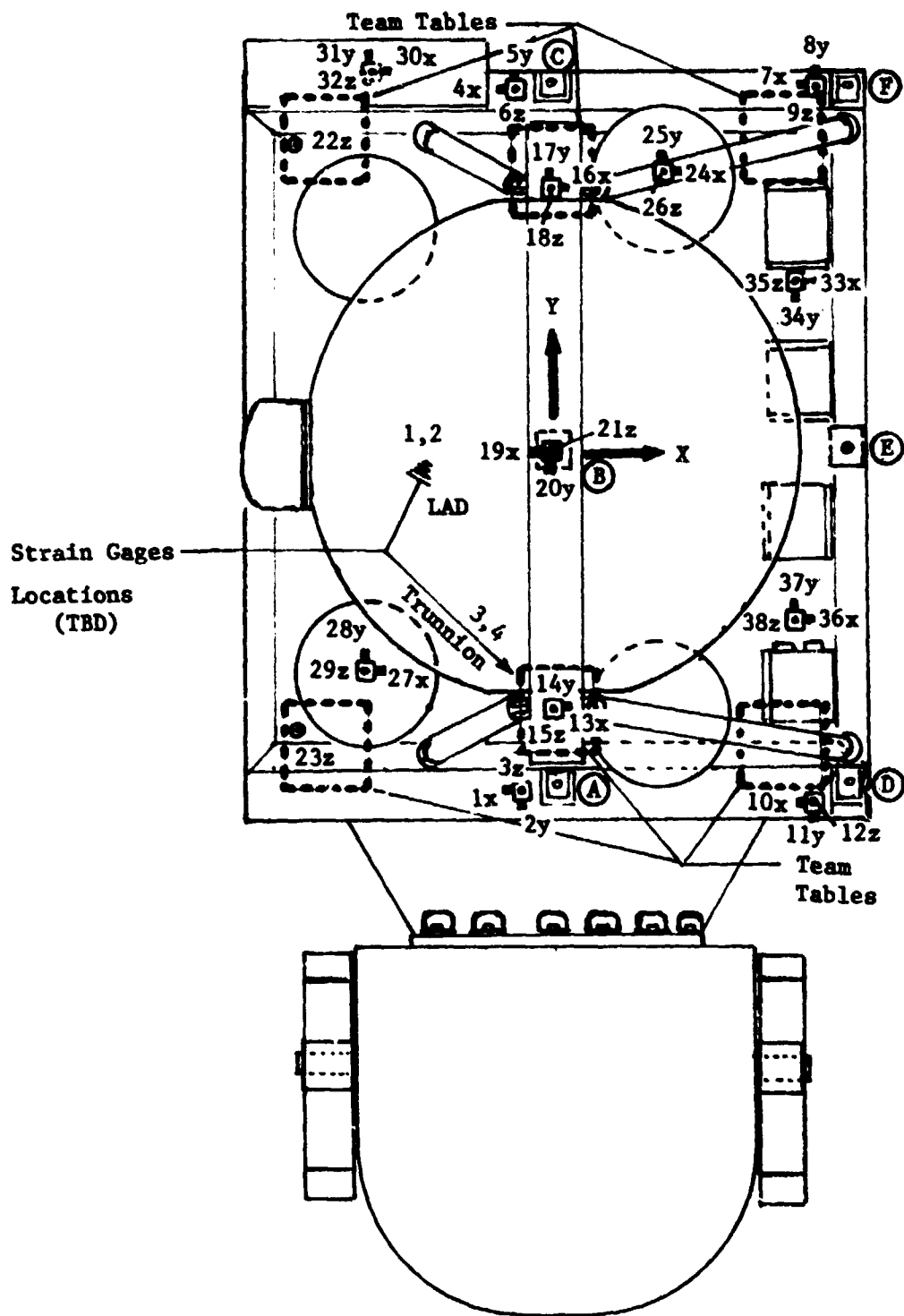


Figure III-25 Lateral (Y) Axis Vibration Test Fixture Configuration

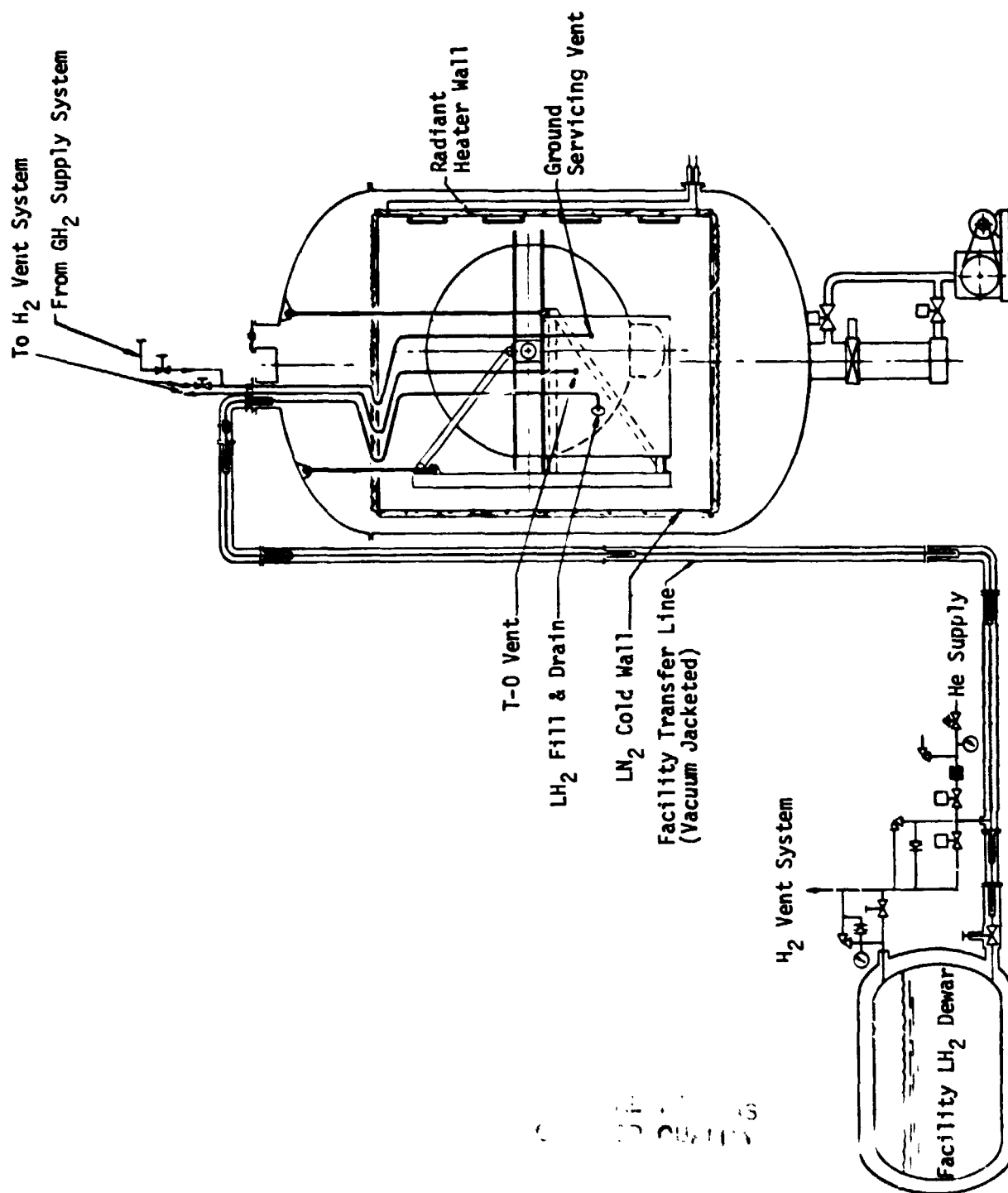


Figure III-26 Thermal Vacuum Test Setup

c. Vacuum Pumps. Various vacuum pumps (both roughing and diffusion) will be used for the establishment and maintenance of vacuum chamber and tank assembly vacuum annulus pressure in the range of 0.01 micron ( $1 \times 10^{-5}$  torr) and 0.001 micron ( $1 \times 10^{-6}$  torr), respectively.

d. Pressurization Systems. Various regulated gaseous helium systems are required at different locations to support test and checkout of the CFME. All Martin Marietta test areas are equipped with GHe at regulated pressures up to  $41480 \text{ kN/m}^2$  (6000 psi). Minor modifications are required to facility GHe systems for CFME support of leak and proof pressure tests, charging of the GHe pressurant spheres, and inerting and purging of the experiment.

e. Weigh Scale. The weigh scale will be used in functional and performance testing to verify CFME loading and draining, calibrate the loads, liquid sensors, orifices, flowmeters and outflow. The scale is a commercial unit with fork lift provisions that accepts the CFME and associated holding or transportation fixtures. The scale has an accuracy of 0.045 kg ( $\pm 0.1$  lbs).

f. LH2 Fill and Drain System. Ground testing requiring LH2 will utilize GSE consisting of the following:

- 1) LH2 supply dewar.
- 2) Vacuum-jacketed fill line.
- 3) Dewar vent plumbing.
- 4) Dewar GHe/LH2 pressurization system.
- 5) Fill line GHe purge.
- 6) Fill line filter.
- 7) System relief protection.
- 8) CFME T-0 vent and ground servicing vent line plumbing.
- 9) Gaseous hydrogen pressurization system.
- 10) Gaseous helium pressurization system.

g. Electromagnetic Compatibility Test Setup. The CFME EMC tests will be accomplished in a RF-shielded room where the CFME is bonded to an RF ground plate. A system functional test will be performed while either subjecting the CFME to the required susceptibility test signals, or measuring the interference generated by the CFME.

## 2. Mechanical Ground Support Equipment/Integration Activity.

a. Lifting and Handling Fixtures. The CFME lifting and handling fixtures consist of slings and structural attachments which are used to position the experiment in either the horizontal or vertical attitude and include a horizontal handling sling, a vertical handling sling, vertical lifting arms, and a vertical test support fixture. All lifting and handling slings and fixtures are Payload Organization (Martin Marietta) supplied GSE. The horizontal handling sling, shown in Figure III-27, consists of a spreader bar and structural base which attaches to the experiment skid at four corner lift points and to an overhead hoist at an adjustable attach location using standard shackles. This sling is used for the positioning and lifting of the CFME in the horizontal position only.

The vertical lifting arms and vertical handling sling are used together, as shown in Figure III-28, to transfer the CFME from the horizontal to the vertical position, and thereafter to lift and position the experiment in the vertical attitude. The vertical lifting arms provide a vertical extension of the skid at the proper point for horizontal/vertical translation and hoisting in the vertical configuration.

A vertical test support fixture is also provided for mounting the CFME in the launch attitude for test and checkout purposes. After the CFME is secured in the fixture the vertical sling and lifting arms may be disconnected.

b. Transportation Skid and Protective Cover. The CFME transportation skid and protective cover are used for transporting and storage of the experiment at the contractor's site and at KSC. Both the skid and the cover are constructed of wood, and configured as illustrated in the sketch, Figure III-29. The skid is composed of a lifting base to which the CFME is mounted, with provision for fork lift points. The protective cover completely encloses the CFME and has provisions to attach to the transportation skid. A lift point ring is provided to facilitate removal of the cover from the skid. The transportation skid and protective cover are Payload Organization (Martin Marietta) Supplied GSE.

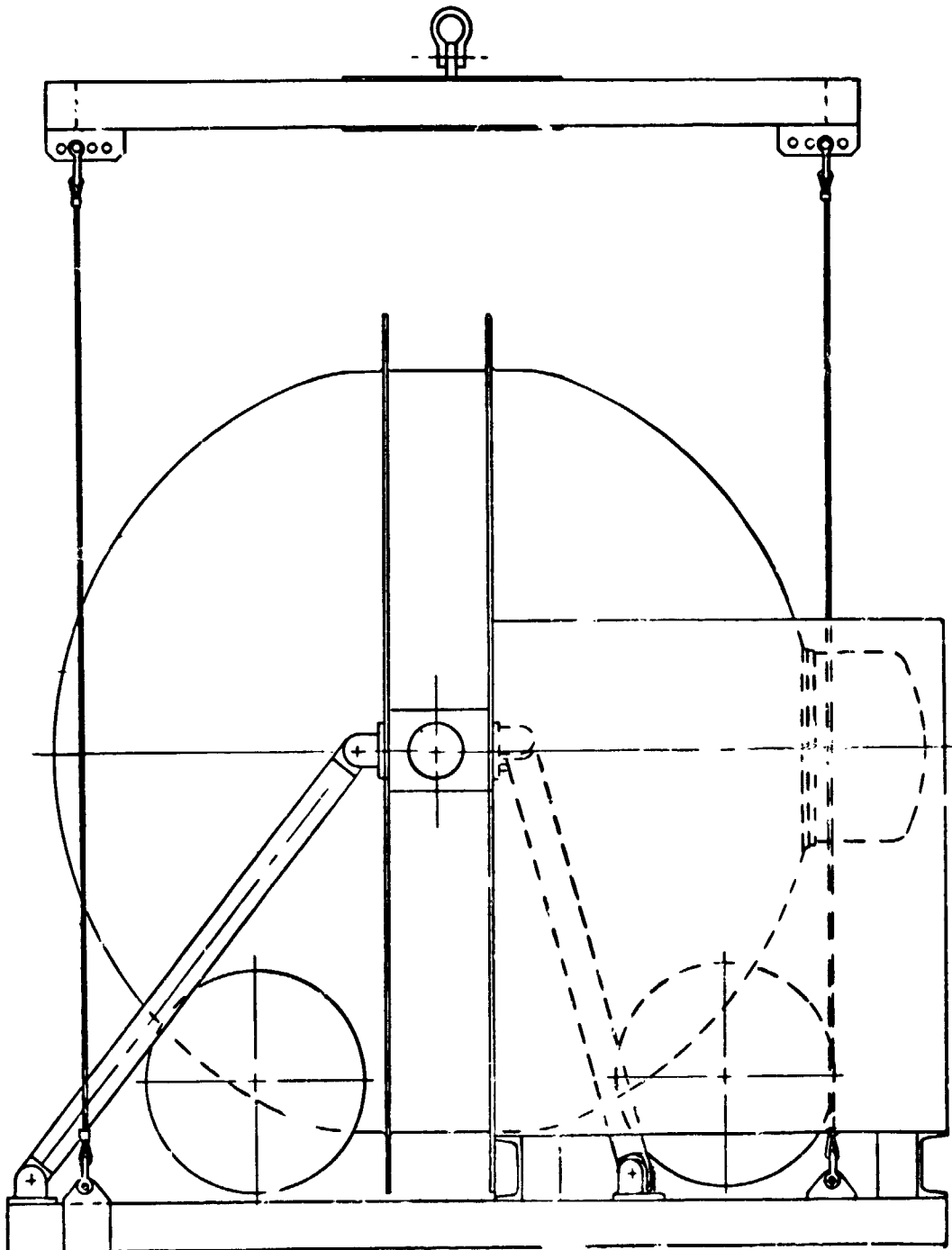


Figure III-27 Horizontal Handling Sling

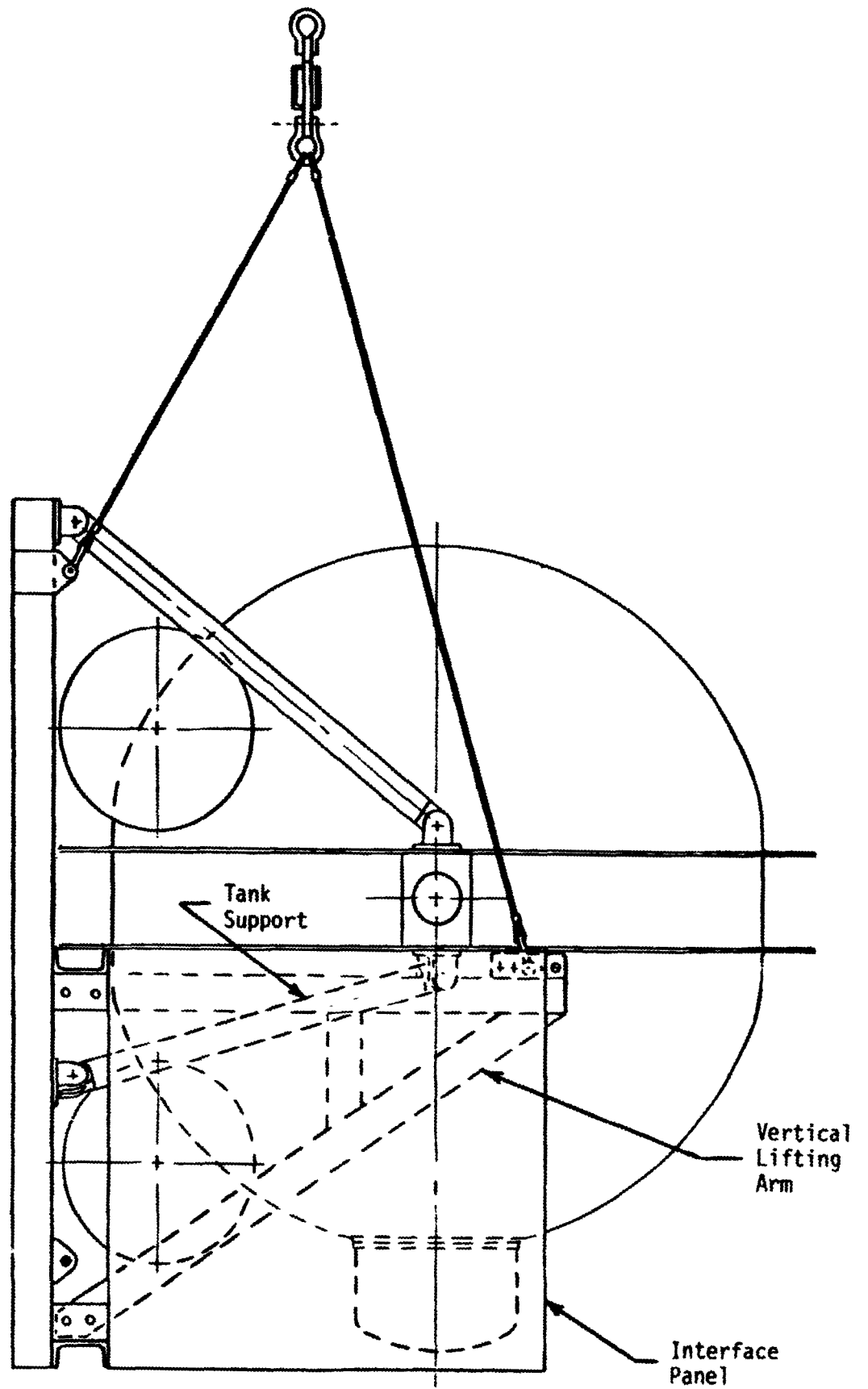
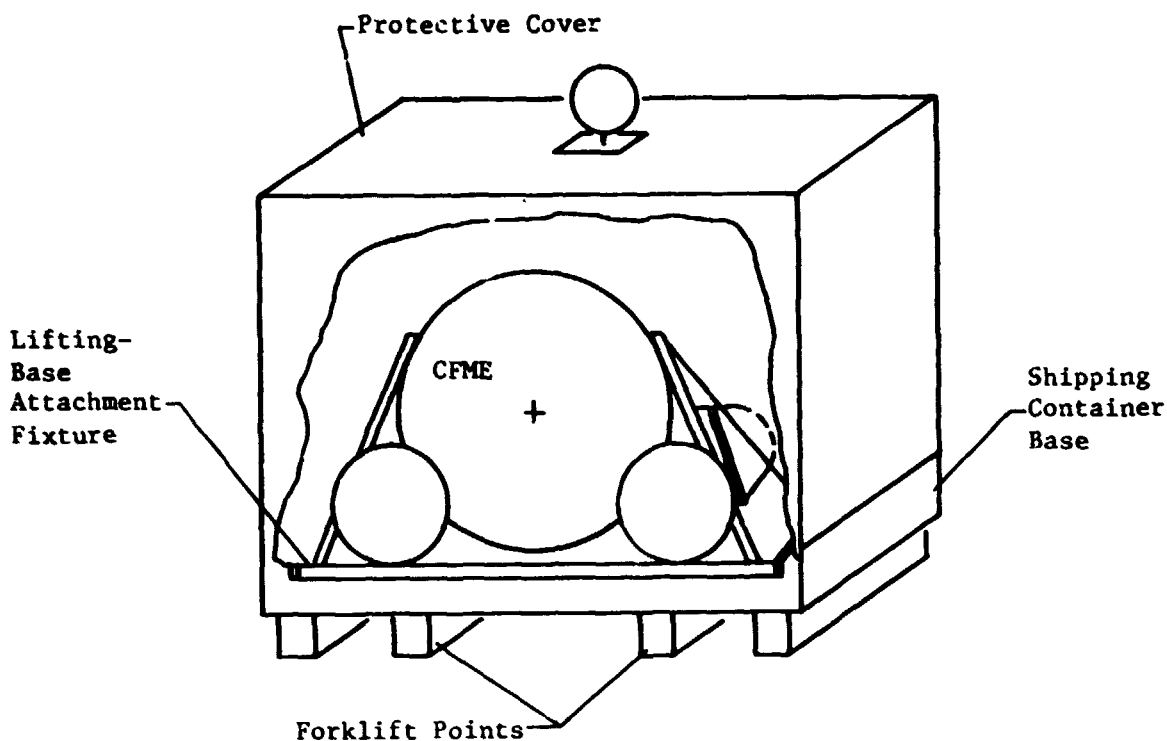


Figure III-28 Vertical Lifting Arm and Sling



*Figure III-29 Transportation Skid and Protective Cover*

3. KSC Supplied GSE. The CFME ground operations flow, from receiving in the Operations and Control (O and C) Building through launch operations, is illustrated in Figure III-30. GSE used for transporting and handling the CFME prior to and during installation on to the Spacelab pallet was defined in the above section. Leak checks, moisture checks, helium sphere pressurization and experiment-specific test and check-out will be accomplished utilizing existing O and C facilities in conjunction with EGSE control. A check of the tank assembly vacuum will be made using KSC available roughing and diffusion pumps, and ionization-type vacuum readout devices. Electrical and mechanical tests of the CFME installation, together with all other payload packages, are made using the Cargo Integration Test Equipment (CITE). This simulates all Spacelab interfaces for the entire payload assembly.

Following complete horizontal integration in the O and C Building, experiment specific GSE is not required until the payload arrives at the launch pad. Installation of the Spacelab pallet into the Orbiter occurs in the Orbiter Processing Facility (OPF), using existing facility handling equipment. Orbiter mechanical and electrical interface connections with the

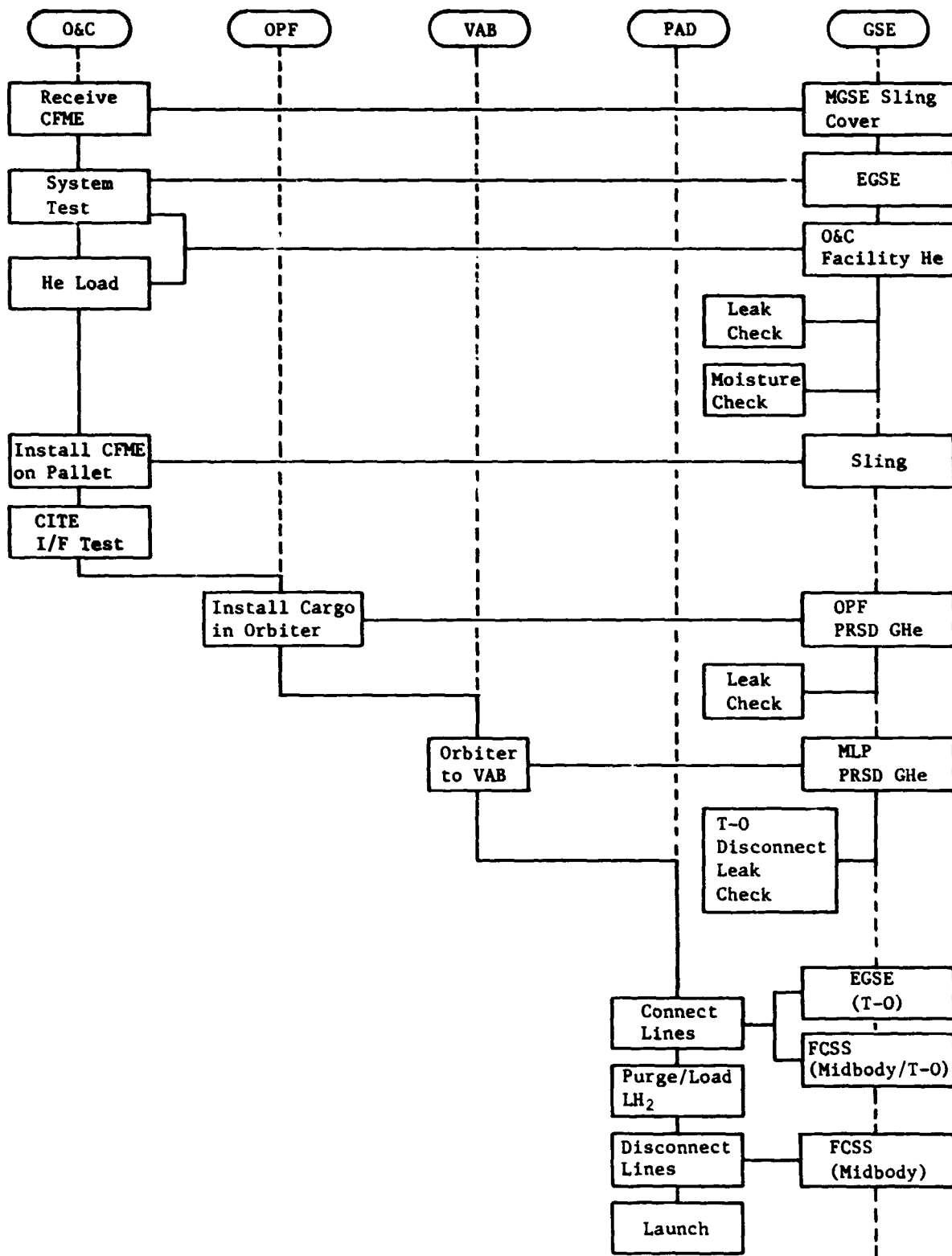


Figure III-30 CFME Flow at KSC



CFME are made at this time. Leak checks of the T-0 umbilical and midbody umbilical interface connections are accomplished utilizing the Power Reactant Storage and Distribution System (PRSD) GSE in the OPF.

The Fuel Cell Servicing System (FCSS) is used to service the experiment while on the pad. Modifications to the FCSS are not required. Rather, procedural changes are made to configure the midbody umbilical flex hoses to support CFME loading at a lower FCSS LH2 dewar pressure than required for the servicing the PRSA tanks.

A new hydrogen vent line is required for the CFME T-0 vent. This line, as shown in Figure III-31, connects to the CFME T-0 vent at the Tail Service Mast (TSM) umbilical interface. The vent line is routed from the TSM to the LH2 Tunnel and runs parallel to the fuel cell GO2 and GH2 reactant gas system supply lines on the Mobile Launch Platform (MLP). A flex hose connection at the Fixed Service Structure/Mobile Launch Platform interface joins the vent line to the GH2 facility vent on the 95-foot level of the Fixed Service structure (FSS). The T-0 vent line will have to be supplied by KSC facilities if not already installed for other payloads prior to the CFME flight. A 1/2-inch line insulated with polyurethane is adequate for handling a 82 kg/hr (180 lbm/hr) LH2 flow rate from the CFME if an emergency abort is required.

Abort landings with a loaded CFME require additional GSE at the runway or in the OPF for CFME safing and deservicing. In the case of runway deservicing, existing Power Reactant Storage and Distribution System detanking GSE will be used. In addition, the requirement for a runway 28VDC power supply for the CFME has been defined since one of the landing modes being considered involves a complete Orbiter power down soon after landing. Under such a circumstance, control of the CFME from both the DACS and the Aft Flight Deck station would be lost. A ground power interface, similar to that which supplies 28VDC ground power for operating the PRSD T-0 O2 and H2 reactant solenoid valves, would be required for CFME control. (The existing power pack for PRSA servicing has limited margin for additional usage such as that required to power the CFME DACS and solenoid valves).

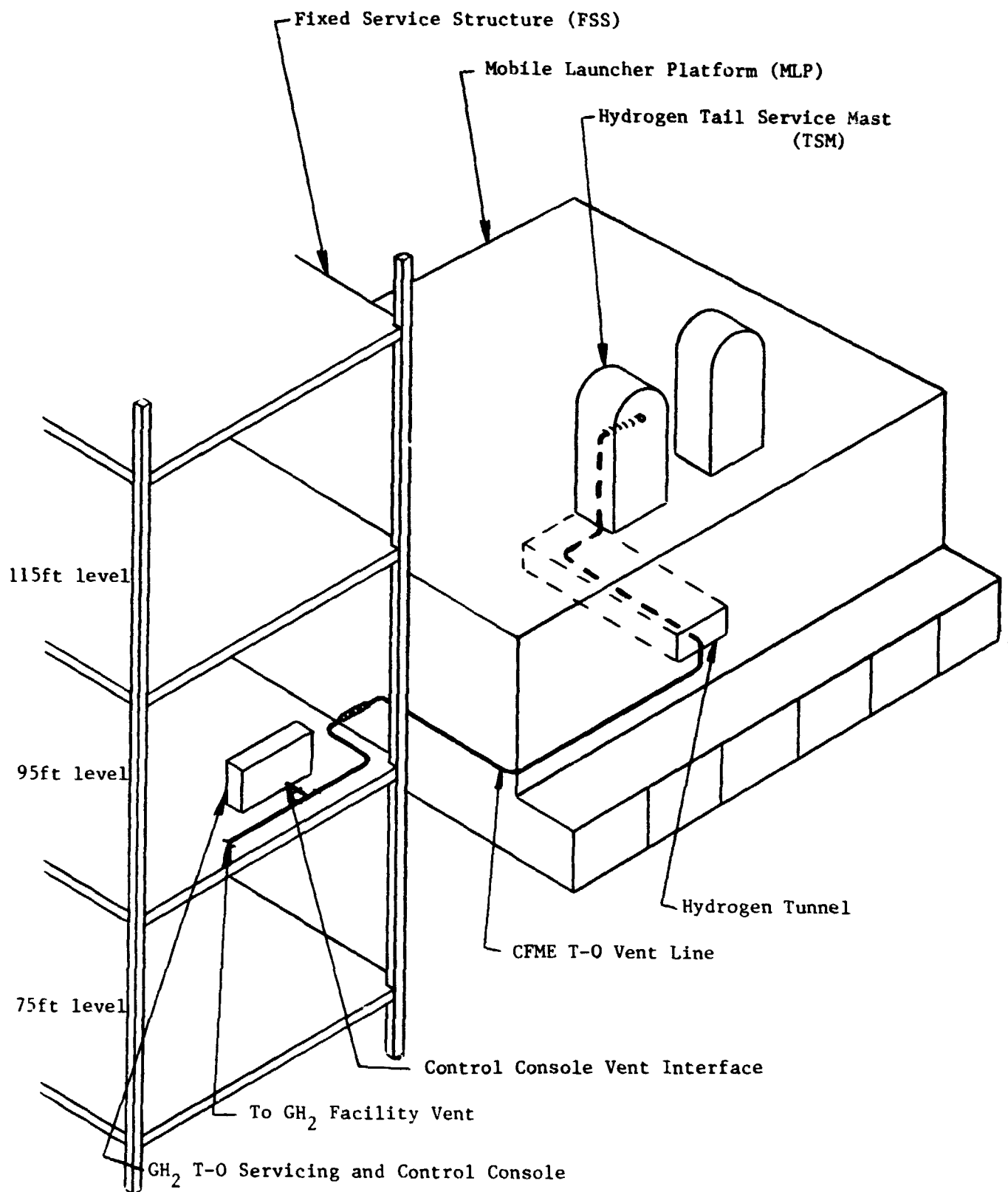


Figure III-31 New CFME T-O Vent Line Configuration

4. Electrical Ground Support Equipment. The electrical Ground Support Equipment (EGSE) in conjunction with the DACS hardware will support functional and environmental tests. A serial bidirectional link between the DACS and the EGSE allows control and monitor of the experiment hardware by the GSE. The EGSE consists of the following major items:

- a) MDS-800 microprocessor development system.
- b) MDS-205 dual Diskette operating system.
- c) MDS-016 RAM, 4 each for total of 64K bytes.
- d) LSI-ADM3 keyboard and CRT display console.
- e) TI-743 KSR line printer.
- f) Special function for DACS hardware test and PROM programming.
- g) Standard Intel 8080 software assembler, loader, and editor.
- h) Mark V, GRU4200 Ground Reproduce Unit.

A block diagram of the system is shown in Figure III-32.

The control capability is provided through predefined operating modes called from the keyboard of the EGSE console by an operator. These modes are implemented in the form of software modules loaded from the GSE into the DACS RAM and executed by the DACS. The EGSE console and Ground Reproduce Unit are shown in Figures III-33 and III-34.

The monitor capability is through the EGSE/DACS link displayed on a CRT and logged or recorded on the printer. The CRT displays readouts of the CFME measurements by title and value in engineering units. Valve status is also displayed. A prime display contains approximately 40 data measurements. The remaining 50 measurements are contained on a secondary display.

Each display is updated approximately once per second. The printed data serves as a permanent record but requires data compression or a much lower sample rate than displayed data. The recommended approach is a combination, logging all measurements once every minute and significant changes as they occur within a one-second resolution. Printed data are tagged with test time to one second resolution.

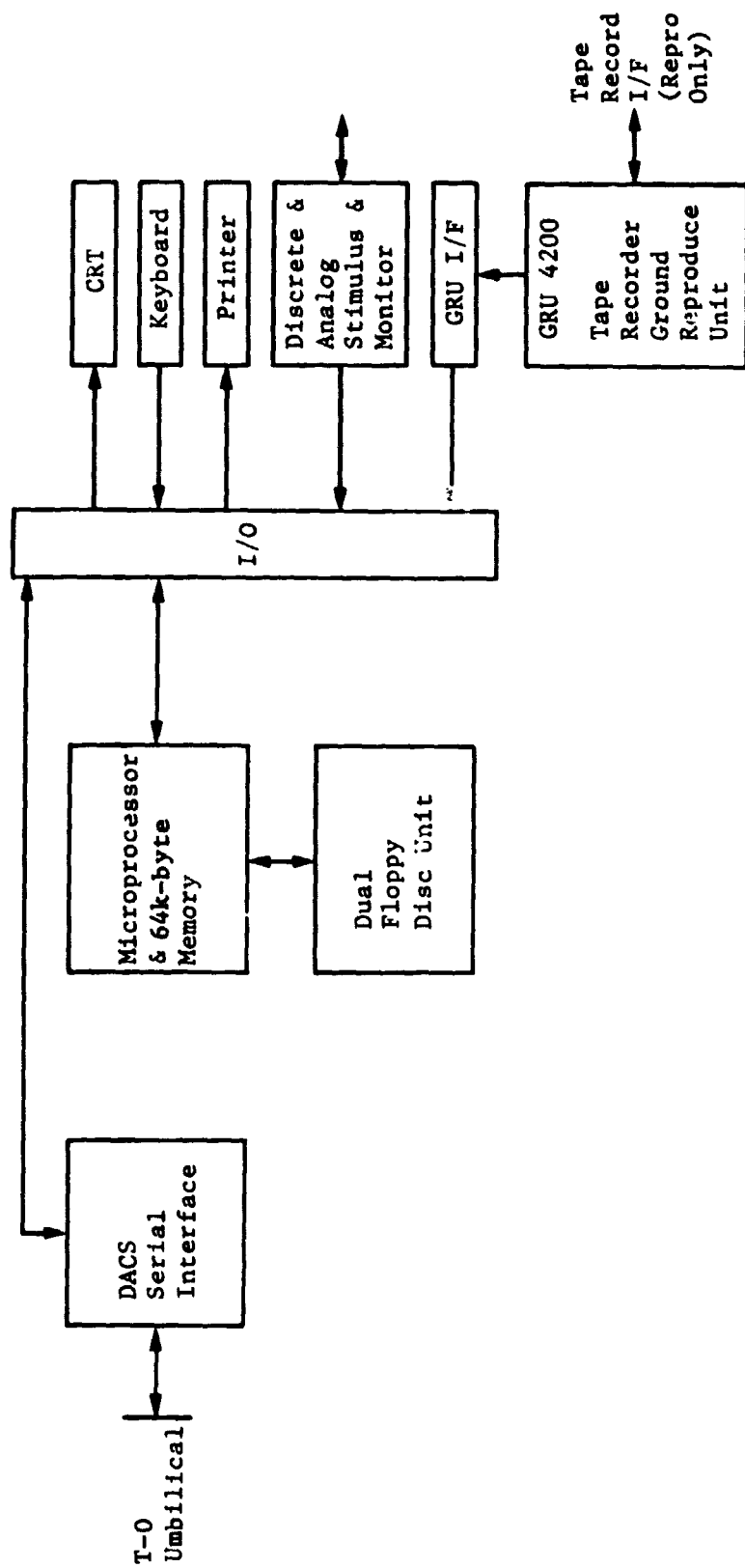


Figure III-32 EGSE Block Diagram

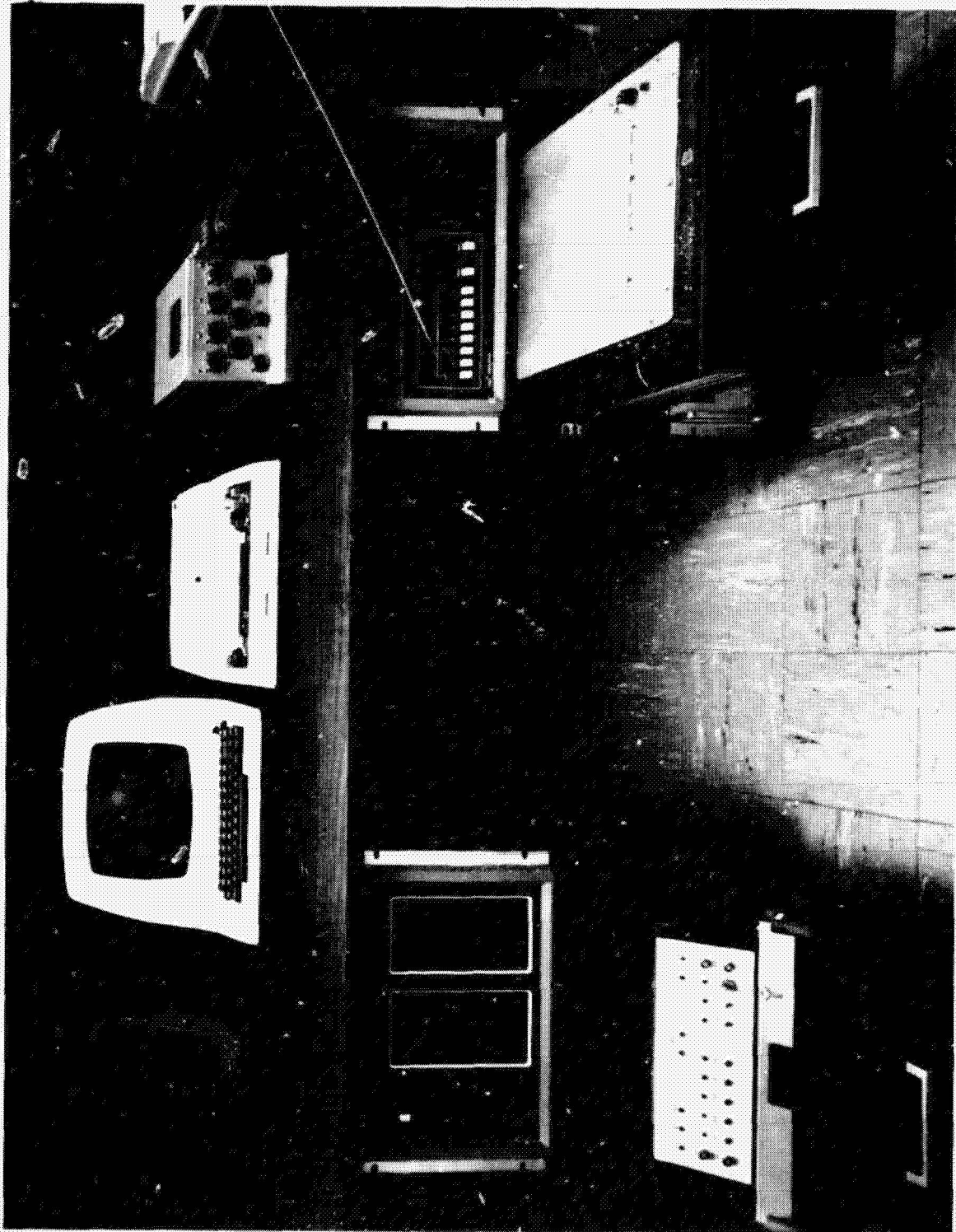


Figure III-33 EGSE Console

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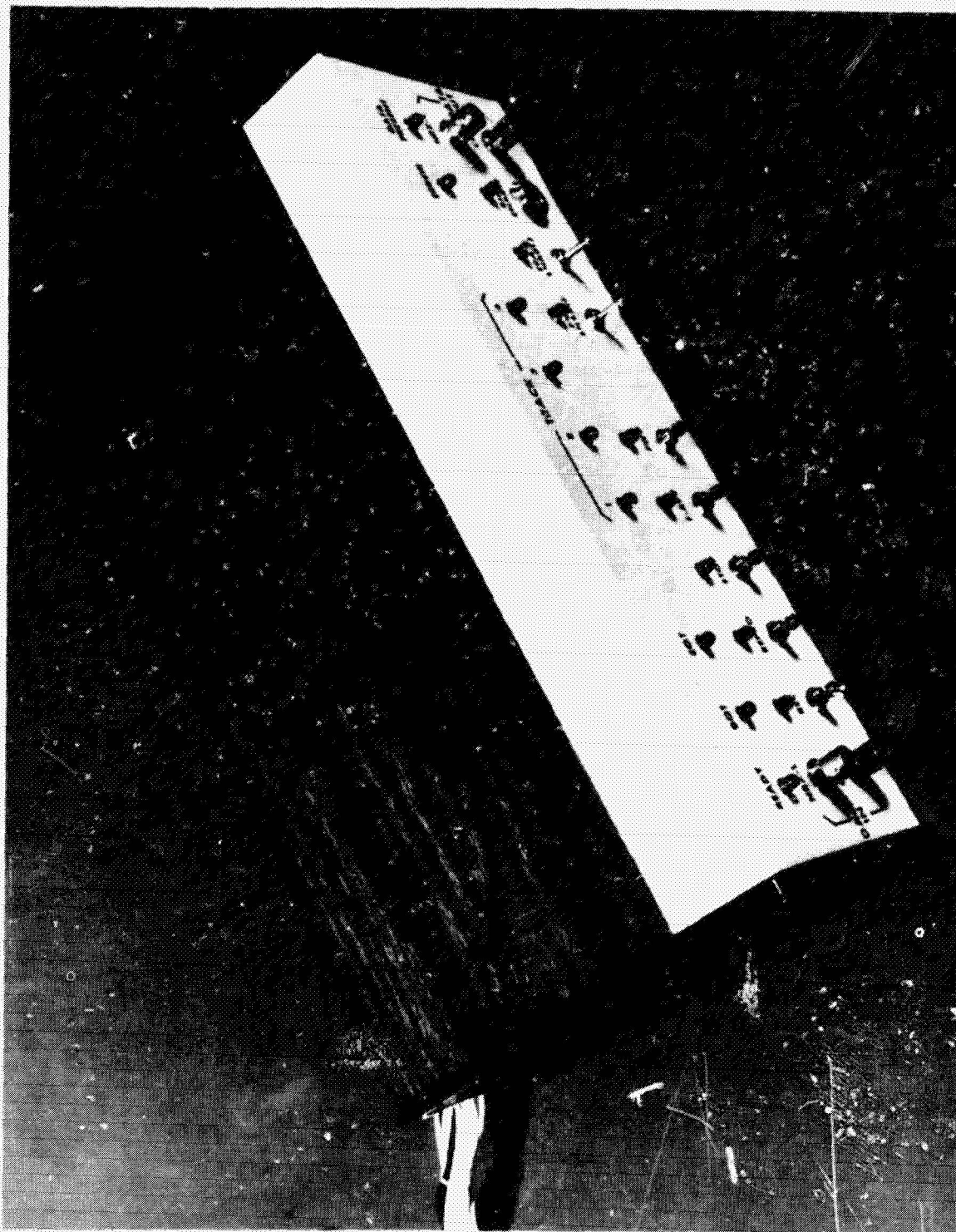


Figure III-34 Ground Reproduce Unit



The pre-launch activities on the launch pad are supported by the EGSE in the same manner as discussed for functional and performance tests. The post-mission GSE function consists of data recovery from the flight tape recorder and data reduction into tabular or graphical form. The GRU4200 Ground Reproduce Unit recovers data from the tape recorder and outputs a serial NRZ signal and synchronous clock. For the data reduction function, however, the baseline approach assumes that NASA facilities can be used for data transfer to Martin Marietta computer-compatible tapes. These facilities, used for other experiments with the same tape recorder and ground reproduce unit, will also be used for CFME data reduction.

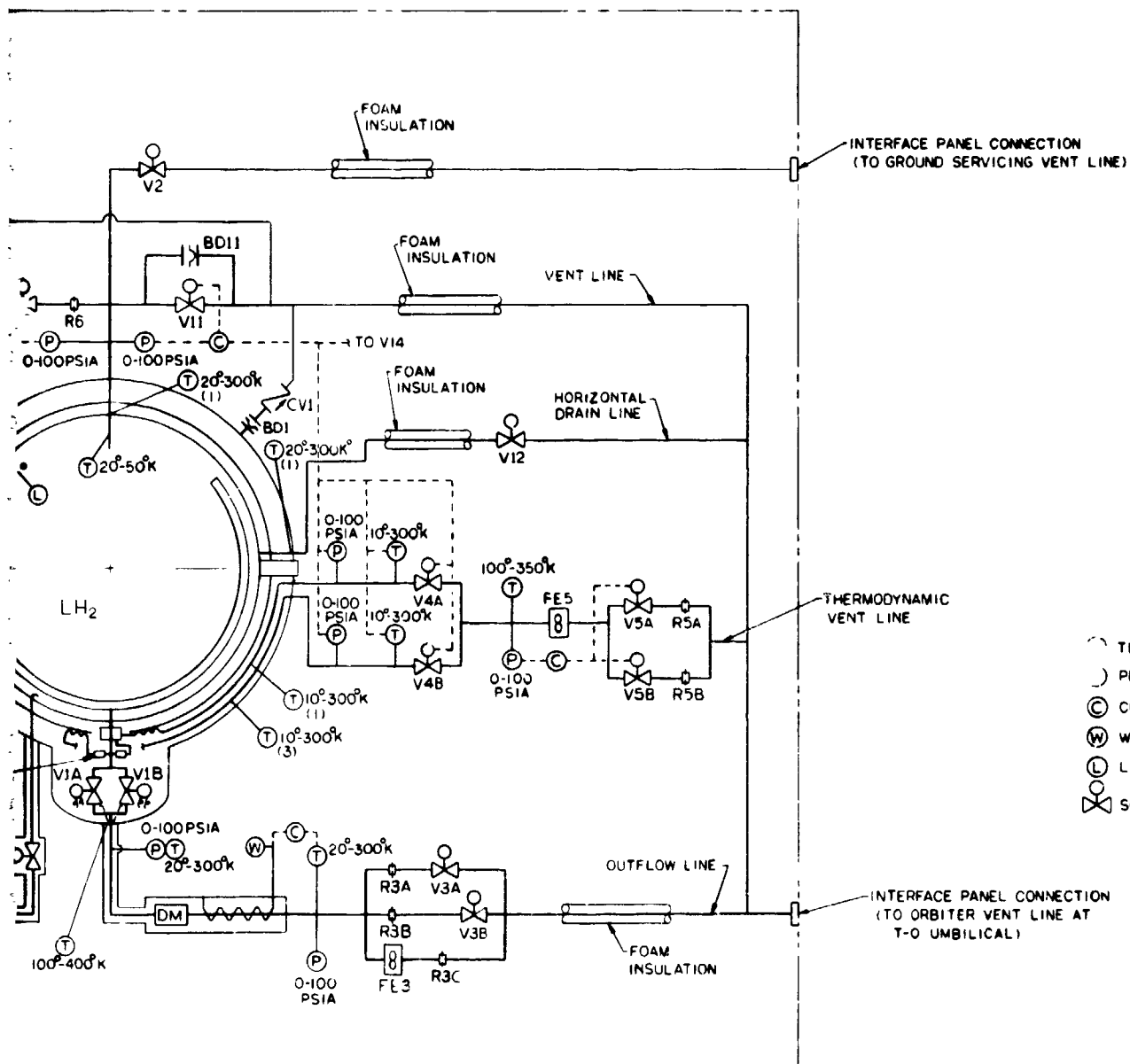
#### D. CFME-TA Description.

The Cryogenic Fluid Management Experiment Test Article (CFME-TA) consists of the systems necessary to support qualification testing of the assembled tank assembly on the experiment pallet. In addition to the tank and its supports, all lines from the tank assembly to the valve panel, along with interface mounts and support structure, will be provided. The valves and burst discs in the valve panel are also a part of the CFME-TA design. The test article, shown schematically in Figure III-35, is composed of the following systems:

- o Liquid Acquisition Device. A surface tension device using fine-mesh screen is used to expel gas-free LH2 from the pressure vessel in the low-g environment.
- o Liquid Hydrogen Tank. A 106-cm (41.7-in) diameter aluminum vessel holds a quantity of 600 liters (160 gal) of LH2 at a maximum operating pressure of  $413 \text{ kN/m}^2$  (60 psia).
- o Vacuum Jacket. An aluminum vacuum jacket surrounds the tank, permitting the annular space to be evacuated. The vacuum jacket is essential to the tank thermal control during launch operations and ascent. It also provides mounting points for the tankage and protection of the Multi-Layer Insulation (MLI).







# LEGEND

⊖	TEMPERATURE	/	BURST DISC
⊖	PRESSURE	⊖	ORIFICE
⊖	CONTROL	⊖	FLOW METER
⊖	WAT FMETER	DM	MASS METER
⊖	LEVEL SENSOR	⊖	CHECK VALVE
⊖	SOLFNOID VALVE		

IER PDU DACS -----EGSE

BOLDOUT FRAME 2

- o Tank Assembly Thermal Control System. A spherical vapor-cooled shield located concentrically between the tank and the vacuum jacket, a thermodynamic vent system and heat exchangers that cool the shield, and multilayer insulation mounted on the shield are included in the tank assembly of the CFME-TA.
- o Pressurization System. Two pressurant spheres, initially filled with helium to  $21600 \text{ kN/m}^2$  (3135 psia) at  $290^\circ\text{C}$  ( $85^\circ\text{F}$ ), together with control valves maintain the liquid hydrogen tank pressure at  $379 \text{ kN/m}^2$  (55 psia) during LH2 expulsion under normal experiment conditions. For the dynamic testing of the CFME-TA, only two pressurant spheres were determined to be needed because of similarity of mounting configuration of the other two spheres.
- o Data Acquisition and Control System. The data acquisition portion of this system includes the instrumentation to measure the CFME-TA performance and provision for signal conditioning and processing. The DACS microprocessor, tape recorder, and power distribution units are mounted off of the CFME-TA pallet and will support testing via test connections.

The interfaces connecting the CFME-TA to test equipment are:

- a) Fill/drain and ground servicing vent lines.
- b) Tank outflow line.
- c) GHe pressurization line.
- d) EGSE Cable
- e) DACS/PDU/Recorder test cables.

#### IV. EXPERIMENT OPERATIONS AND SAFETY

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##### A. Ground Operations.

The operating modes for the CFME are described in this section and include ground operations and checkout, prelaunch, launch, and abort operations. The ground operations are discussed in greater detail in the CFME Launch Site Operations Plan (Ref. 7). The CFME flow at KSC was illustrated in Figure III-30.

1. Ground Handling and Shipping. The CFME will be shipped to KSC in a special container designed to MIL-STD-794. A transportation skid and protective cover, both of which are Payload Organization (Martin Marietta) supplied GSE, are included for ease of handling and protection at KSC. The skid is composed of a lifting base with provisions for fork lift points. A lift point ring to facilitate removal of the cover from the skid is provided.
2. Receiving and Inspection. After a visual inspection of the protective cover and transportation skid is performed, the cover can be removed and the CFME can be disconnected from the skid. The horizontal handling sling consists of a spreader bar and structural base which will attach to the experiment skid at four corner lift points and to an overhead hoist at an adjustable attach point location using standard shackles. This sling is used for the positioning and lifting of the CFME in the horizontal attitude. A vertical handling sling will also be delivered for contingency rotation of the CFME from the horizontal to the vertical attitude. In addition to the vertical handling sling, a vertical lifting arm and a vertical test support fixture are provided.

The following operations will be performed on the CFME to ensure that nothing was damaged during shipping. (All operations are performed in the High Bay area of the O and C Building.)

- a. A visual inspection of the entire experiment.
- b. Check of system pad pressure levels and removal of any associated GSE for measuring pad pressure.
- c. A check of the LH<sub>2</sub> tank vacuum, and vacuum-jacketed lines.

- d. Connect the Electrical Ground Support Equipment (EGSE) to the CFME and perform an electromechanical check of the experiment to verify proper function of all subsystems.

3. Payload Integration Operations. Using the horizontal handling sling the experiment package is mounted on the designated Spacelab pallet. The pallet is then mounted in the Spacelab payload assembly.

The following operations are performed on the CFME while installed on the Spacelab pallet in the O and C Building.:

- a. Connect the two Power Distribution Unit (PDU) cables to the Spacelab pallet electrical interface.
- b. Connect the EGSE to the CFME to assist in integration checkout.
- c. Connect CFME fill/drain, ground servicing vent, and T-O vent lines (from the CFME interface panel) to the Spacelab fluid mechanical interfaces.
- d. Perform electrical continuity checks and plumbing interface leak checks and moisture checks using the Cargo Integration Test Equipment (CITE) and the EGSE.
- e. If the orbital flight plan will result in excessive solar heat flux to the CFME, installation of the experiment protective thermal shroud will be accomplished at this time.
- f. Service the CFME helium spheres to  $21600 \text{ kN/m}^2$  (3135 psia) using GHe sampled to SE-S-0073, Table 6.3-1 (Ref. 8). The O and C Building facility GHe system will be used as the supply for this operation with pressure regulation provided by the facility GHe regulation panels.
- g. Apply a pad pressure to the LH2 tank of  $69\text{--}103 \text{ kN/m}^2$  (10-15 psig) GHe for installation into the Orbiter.
- h. Disconnect the EGSE, CITE and GHe servicing equipment from the CFME.
- i. Transport the EGSE to the Launch Control Center (LCC) to support the next CFME powered operation.

4. Pressurant Sphere Servicing. Charging the CFME helium spheres is a hazardous operation and should be delayed until just prior to loading the Spacelab pallet into the Payload Canister for transportation to the Orbiter Processing Facility (OPF). After the spheres are serviced, special handling

provisions should be initiated with precautions to limit personnel access in the vicinity of the spheres. These controls should remain in effect for the duration of CFME ground operations.

5. Orbiter Payload Installation Operations. After the Spacelab pallet containing the CFME is installed into the Orbiter cargo bay, the following mechanical and electrical connections will be made:

- a. LH2 fill/drain to the midbody umbilical
- b. Ground servicing vent to the midbody umbilical
- c. T-O umbilical/Orbiter vent to the hydrogen T-O umbilical
- d. EGSE cable connection to the T-O umbilical
- e. OCP cable connection on the Aft Flight Deck
- f. 28 VDC abort landing ground power connection

The following verification checks of the final interface connections will be made:

- a. Continuity checks of electrical connections
- b. GHe leak checks using a mass spectrometer with GHe supplied by the Orbiter Power Reactant Supply and Distribution System (PRSD) GSE (S70-0815 and S70-0698 systems). CFME line pressurization will be accomplished via connections at the midbody and T-O umbilicals.

6. Vehicle Assembly Building Operations. Following mating of the Orbiter to the External Tank and Solid Rocket Boosters in the VAB the T-O umbilical carrier plate is mated. Then all fluid mechanical airborne/ground disconnect seals have to be leak checked. The leak check of the CFME T-O umbilical/Orbiter vent connection will be accomplished using the gaseous helium tube bank used for the leak check of the fuel cell T-O hydrogen disconnect. Pressure will be applied at the Mobile Launcher Platform (MLP)/Fixed Service Structure (FSS) interface to a value of 413 kN/m<sup>2</sup> (60 psia).

7. Launch Pad Activities. All checkout, loading, topping, and contingency off-loading are operations which will be accomplished once the integrated Shuttle is transported to the Pad.

Installation of the EGSE into the LCC and checkout of the console and the pad cable links to the CFME will be accomplished while the Orbiter is in the OPF and VAB. The following operations will have to be performed after the Orbiter arrives at the pad:

- a. Make the flexhose connection from the MLP T-0 umbilical vent line to the FSS hydrogen vent on the 95 foot level.
- b. Mate the pad EGSE cable to the MLP EGSE cable for DACS control.
- c. Configure the Fuel Cell Servicing System to support CFME LH2 loading.
- d. Mate the midbody umbilical to the Orbiter.

KSC has indicated the desirability of using the Fuel Cell Servicing System (FCSS) to load the CFME, as shown in Figure IV-1, and doing the hazardous servicing of the CFME prior to servicing the Power Reactant Supply Assembly (PRSA) tanks which feed the Orbiter fuel cells. Preliminary timelines for the first several Shuttle flights indicate that PRSA servicing may start as early as 15 hours prior to launch. CFME servicing would then start approximately 18 hours prior to launch. A CFME hazardous servicing timeline corresponding to these time constraints is shown in Figure IV-2 and represents a typical time-sequencing which is subject to change as Orbiter ground servicing requirements dictate.

A pulse-purge of the hydrogen storage vessel with ambient gaseous hydrogen from the FCSS will precede loading of the tanks with liquid hydrogen. A moisture check will also be made prior to liquid loading. The DACS will be operated by the EGSE, and will in turn control operation of the CFME valves. The EGSE and control panel for the FCSS are located in the Launch Control Center (LCC). Data monitoring and collection will be performed through the EGSE.

Liquid loading will be accomplished at a dewar pressure of 34-138 kN/m<sup>2</sup> (5-20 psig), and the vented hydrogen for cooldown routed through the experiment vent line to the FCSS disposal stack. Liquid loading will continue until liquid overflow enters the pressurant diffuser tube on the end of the tank vent penetration. Monitoring of the liquid level sensors and the vent standpipe temperature sensor will confirm liquid loading to the 95 percent level. A total of 30 minutes has been allocated for cooldown and loading.

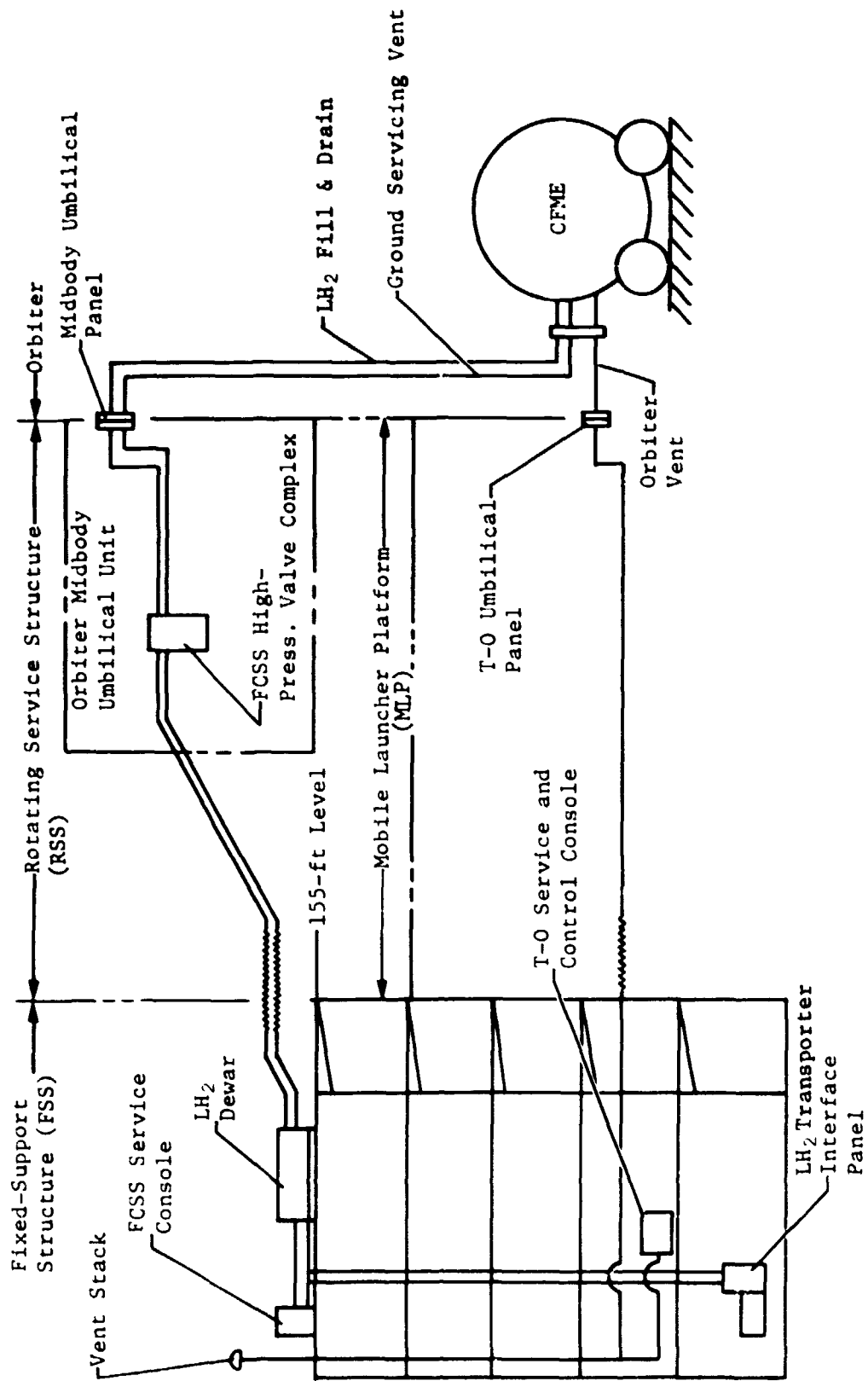


Figure IV-1 CFME Servicing Concept Using the Fuel Cell Servicing System

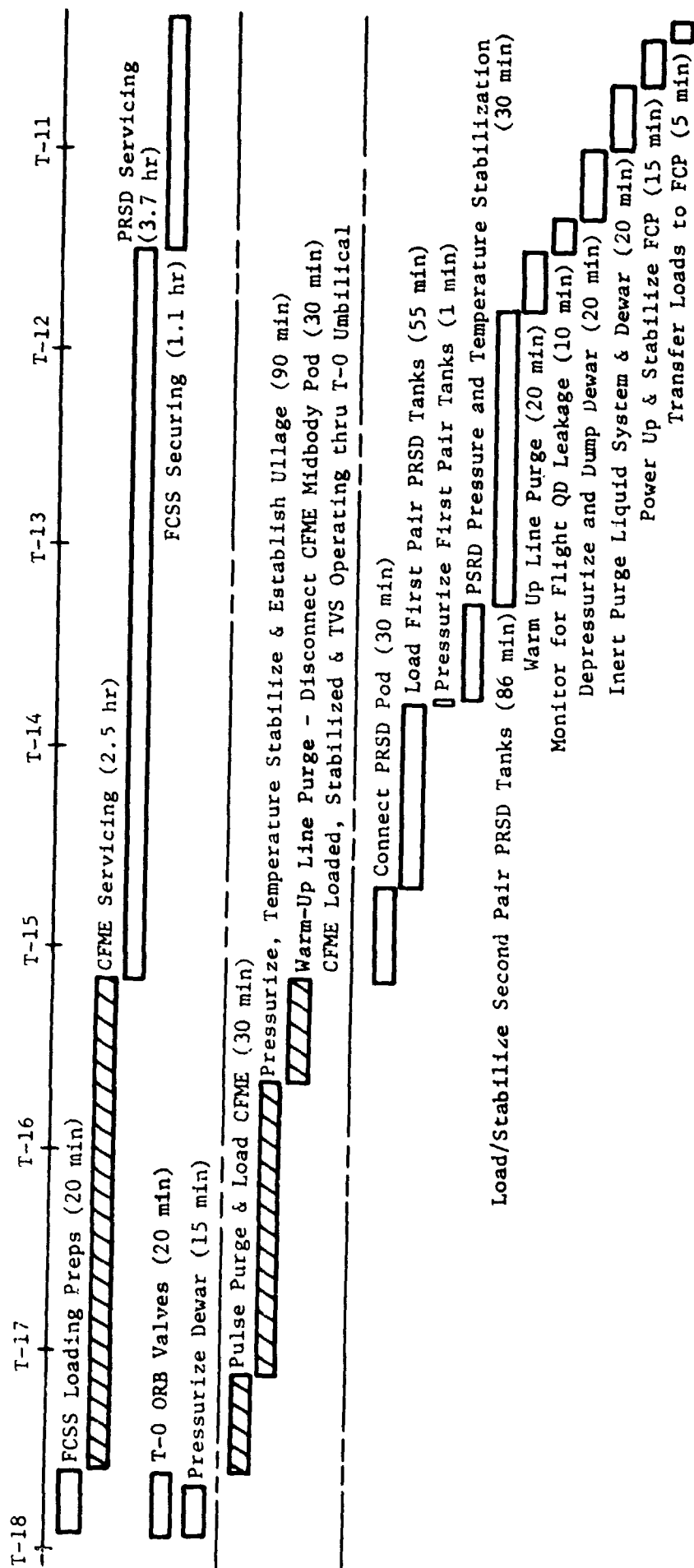


Figure IV-2 Representative Hazardous Servicing Timeline



An additional 90 minutes has been designated for pressurizing, temperature stabilization and establishing a final liquid level prior to disconnecting the midbody umbilical panel. Pressurizing the tank to  $207 \text{ kN/m}^2$  (30 psia) through the ground vent line with gaseous hydrogen from the FCSS is required to collapse any vapor that may have been trapped in the acquisition device channels during tank loading. Once  $207 \text{ kN/m}^2$  (30 psia) has been reached, pressurization ceases and the tank is allowed to come into thermal equilibrium. During this entire sequence, vented gaseous hydrogen from heat exchanger 1 is routed to the T-0 umbilical and out the CFME T-0 vent line (see Figure III-31). Following final tank topping, and verification by the upper level sensor that the tank is loaded to the desired 95 percent level, the midbody umbilical panel is disconnected and a manual close out of the hydrogen fill/drain and vent line disconnects is made.

Flow through the thermodynamic vent heat exchangers is vented overboard through the T-0 umbilical interface until lift-off. Heat exchanger number one is flowing continuously, and heat exchanger number two only vents as required to preclude vapor transfer back into the LAD. An estimated 72 hours of hold capability with continuous TVS venting is available before tank retopping is required. The tape recorder is turned on just prior to lift-off to be sure that data associated with launch transients are obtained.

8. CFME Launch Pad Power. During ground operations, the CFME will be powered through the regular Orbiter/Spacelab interfaces. This is ground-supplied power and not that generated by the Orbiter fuel-cell power supply system. When the Orbiter is switched to internal power, the CFME must still receive power, and this will be supplied by the essential bus since Spacelab power is not activated until after orbit has been reached. Since the CFME is in a storage and thermal stabilization mode, only the DACS, tape recorder and TVS vent valves are powered under normal operating conditions during this period. This represents a minimum CFME demand on the essential bus power allocations.

9. Launch Pad Contingency Operations. As mentioned previously, control of the DACS while sitting on the pad is provided through the DACS EGSE. Outflow at any time can be initiated through the EGSE. Since the CFME helium pressurization spheres are serviced prior to the payload arriving at the pad, it is desirable not to use pressurant from this supply for detanking

hydrogen. Instead, if the tank needs to be drained on the pad, the procedure will be to back-pressurize with warm hydrogen gas through the ground servicing vent line with valves V10 and V2 open, and drain through the fill and drain line. GSE will have to be hooked-up at the midbody umbilical interface to route the hydrogen away to the vent stack. Pressure control through the ground vent line must be maintained at a level of  $379 \text{ kN/m}^2$  (55 psia) or less to prevent tank overpressure and resulting vent relief through the relief valve V11 or the burst disc BD11.

If an emergency condition exists where time is not available to attach the appropriate lines for draining at the midbody umbilical, then the stored helium pressurization system can be activated and controlled by the DACS, through the DACS EGSE, to empty the tank. Outlet line valves V1A and V3A will be opened and liquid expelled through the T-0 umbilical vent line using the GHe pressurization system to expel the liquid. It should be noted again, however, that this is an alternate operating sequence that should only be used as a backup mode since no provisions exist to provide for GHe tank servicing at the pad.

During the prelaunch activities, it has been assumed that the crew is not on-board the Orbiter and there is no access to the manual backup switches for emptying the tank. In case the electronics were lost and the DACS became inoperative, the tank could still be drained by blowdown, with liquid flow back through the LH2 fill and drain line (assuming valve V10 was open or could be opened prior to loss of power.)

A chart indicating how malfunctions and/or aborts are handled automatically through the EGSE is presented in Figure IV-3. Ground operations are considered in this figure and represent operations once the CFME has been loaded, as verified by the EGSE.

10. Post Landing Runway Operations. An on-orbit abort resulting in a return with a loaded tank represents the situation where off-loading cannot be accomplished either within a fixed time constraint or because other abort-related activities, such as dumping Shuttle RCS propellants, would be further complicated by the dumping overboard of a large quantity of hydrogen. Early in the mission, when this type of abort is likely to occur, the

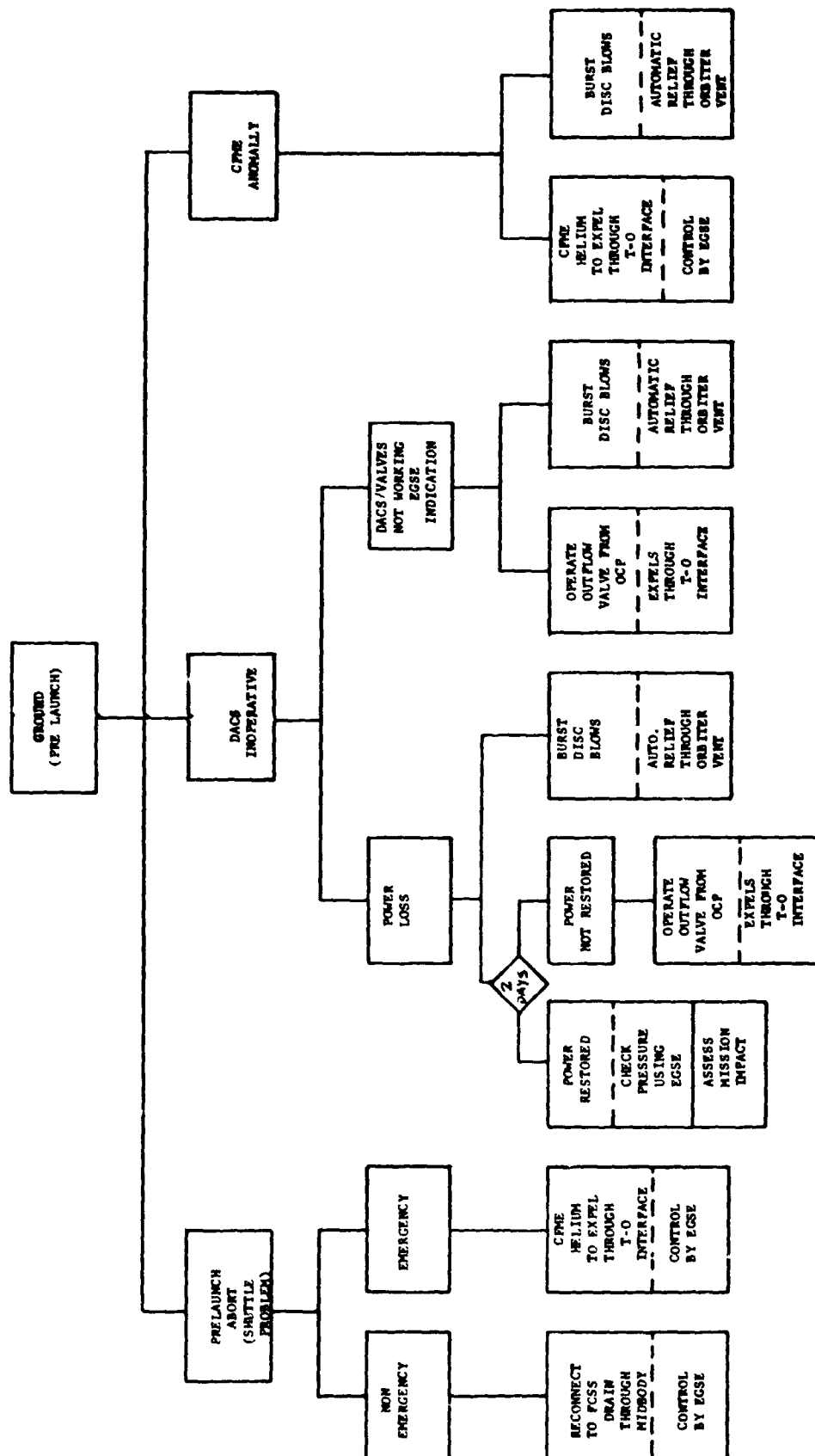


Figure IV-3 Ground Abort and Malfunction Decision Chart

experiment is being controlled automatically through the preprogrammed sequence by the DACS. The thermodynamic vent heat exchanger(s) is the active, functioning subsystem of the experiment hardware during this portion of the mission. This subsystem will continue to function throughout entry and landing. The hydrogen vent rate through the overboard vent during TVS operation is on the order of 0.014 to 0.032 kg/hr (0.03 to 0.07 lb/hr).

Following landing, when the Orbiter is in the horizontal, rollout attitude, horizontal draining of the tank can be accomplished. The horizontal drain operation is activated by the horizontal drain switch on the Aft Flight Deck CFME Operation Control Panel. The switch will signal the DACS to execute the preprogrammed horizontal drain sequence. The DACS will regulate the helium pressurization subsystem to accomplish the draining at a rate of 81.6 kg/hr (180 lb/hr). Portable GSE presently available at KSC for horizontal draining of the fuel cell supply tanks is planned to be used for off-loading of the CFME tank through the T-0 umbilical. Modifications to this GSE are required in order to provide for safe venting of CFME hydrogen through the portable vent stack while the fuel cell cryo tanks are being drained. Provisions for the interface of this GSE with the CFME T-0 umbilical disconnect must also be coordinated. Activation of the horizontal drain sequence requires initiation from the Aft Flight Deck, and no separate control from the portable GSE is planned. However, for the instance where fuel cell power is shutdown on the runway, a portable 28 VDC ground power supply will have to be connected to the CFME at the T-0 umbilical for experiment control via the OCP. Inerting with helium follows hydrogen draining, and the GSE can be removed and the DACS powered-down at this time.

An alternate to using the portable GSE on or near the runway is to retain liquid within the tank until the Orbiter has been moved to the OPF, where draining and venting through the OPF stack is permitted. Modifications to the OPF Power Reactant Storage and Distribution (PRSD) system GSE drain is required to accomplish this contingency task.

11. CFME Removal and Storage. The Spacelab pallet containing the CFME will be removed from the payload bay and returned to the O and C Building after the Orbiter systems are deserviced and safed. Here the CFME would either be removed from the Spacelab pallet or left on and prepared for a future flight.

In either case, however, the flight data will be obtained by connecting the Ground Reproduce Unit to the playback interface on the tape recorder. If the CFME is removed from the Spacelab pallet, the following operations will be performed prior to storage in the protective cover:

- a. Inspect the entire experiment for any flight damage.
- b. Purge the LH2 tank with GHe to ensure that residual hydrogen is removed.
- c. Establish a pad pressure of 172-345 kN/m<sup>2</sup> (25-50 psig) in the helium spheres and 69-103 kN/m<sup>2</sup> (10-15 psig) in the LH2 tank.

The above operations will also be accomplished if the CFME is left mounted on the Spacelab pallet.

12. Safety. Currently there are five potential hazards identified in Attachment III of the Phase I Ground Safety Compliance Data Package (CFME-80-5) dated March 31, 1980 (Ref. 9). All are associated with hazards which are intrinsic to the CFME Ground Support Equipment and its related interfaces/operations, including hazard causes and hazard controls. The potential hazard causes and corresponding hazard controls are summarized in the following paragraphs.

- a. The Fuel Cell Servicing System (FCSS), which supplies liquid hydrogen to the CFME, does not remain leak tight and spills occur and/or inadvertant hydrogen venting is permitted. Personnel may be exposed to frost burn or toxicity hazard and equipment may be damaged by contamination/fire. This hazard may be caused by either of the following:
  - o Personnel errors/equipment anomalies occur during liquid hydrogen loading and/or off-loading.
  - o Off-nominal hydrogen venting occurs at the launch site and/or at alternate landing sites following an Orbiter abort.

Control of this hazard may be accomplished as follows:

- o All contractor personnel performing critical CFME functions will be trained/certified to recognize potential hazards and to

- prevent their occurrence via operational means. All CFME test personnel will be trained/certified per launch site requirements.
- o All CFME checkout procedures for use at the launch site which control hazardous operations will be designated accordingly and will comply with NASA-KSC-K-STSM-14.1, Section VI on Hazardous Activities, and KMI 1710.13A for Safety Review of Operating Procedures.
  - o The CFME will be designed and tested to minimize any potential for leaking and/or off-nominal venting. Liquid hydrogen loading/off-loading activities will comply with KSC-K-STSM-14.1, Section 6.6.2 and 6.5, c and d. The CFME fill and drain, and ground servicing vent system will interface with the Fuel Cell Servicing System through the Orbiter midbody umbilical panel. The CFME loading/off-loading function will be conducted using the FCSS. Interfacing with this system will be a procedural function and will utilize existing vent, isolation and relief valves. The CFME Orbiter vent line interfaces through the T-0 umbilical panel, and connects to a ground vent line which feeds into the stack downstream of the control panel and plumbing which supplies fuel cell reactants to the Orbiter (through the T-0 interface).
  - o CFME hydrogen storage vessel venting following an Orbiter abort is considered to be sufficiently controlled; accordingly there is no unacceptable risk in venting after landing.

RTLS Abort. Insufficient time is available to dump the hydrogen. Thermodynamic vent system valves will control venting and as a redundancy or back-up the relief valve and burst disc is available. Portable GSE is available to detank the hydrogen after landing.

Abort to Alternate Landing Site. Liquid hydrogen will be vented/dumped prior to landing as part of the normal mission timeline. Should some Orbiter on-orbit abort operational constraint preclude emptying all the hydrogen, there will be no risk in landing with liquid hydrogen still in the tank since we are designed to contain.

Once on the ground a small amount of hydrogen would be vented overboard through the vent (at the T-0 umbilical) on a continuous basis to maintain tank pressure below the relief level of  $414 \text{ kN/m}^2$  (60 psia).

- b. Mate/Demate of CFME electrical Ground Support Equipment connectors could cause personnel electroshock injury. This hazard may be caused by either of the following:
  - o Electrical connectors (specifically male pins) are "hot" during mate/demate activities.
  - o Electrical system checkout and activation not under specific procedural control.

Control of this hazard may be accomplished as follows:

- o The CFME electrical Ground Support Equipment will be designed to preclude the existence of "hot" male pins. This design provision will comply with NASA-KSC-K-STSM-14.1, Section 6.6.7 for the intent of explosion proofing and JSC 11123, 3.4.1.1 for connector design.
- o Controls have been stipulated which provide for a leak tight liquid hydrogen system and the absence of explosive vapors. This requirement in combination with meeting electrical explosion proofing criteria minimizes the hazard. All CFME test and checkout will be under stringent launch site procedural control. Typical of those controls which will be reflected in the CFME procedures are:

Stamped on face of procedure – "This procedure contains hazardous operations."

WARNING – Electrical connectors shall not be mated/demated until it has been verified that no power is applied.

**CAUTION** - Hydrogen vapor detectors shall be utilized during initial hydrogen loading and/or any off-loading.

Launch site procedures will also specify that connector mate/demate will not be permitted if hydrogen vapors are present in any one area.

- c. CFME may be damaged via impact with other hardware. Impact damage on the helium spheres could introduce pre-stressing and subsequent leaking/rupture when pressurized. This hazard may be caused by any of the following:

- o Handling equipment not compatible at the CFME interface. Handling equipment bears against the helium spheres and introduces potential leaks via stress concentration.
- o Damage not detected; leaks/rupture occur in the pressurization system during helium leak test.
- o Personnel are not sufficiently trained/certified.

Control of this hazard can be accomplished as follows:

- o Handling equipment to be used with the CFME will be specially designed for its purpose. The equipment will be proof tested and tagged before it is shipped to the launch site, and will include associated documentation to certify this condition. This equipment will comply with applicable portions of NASA-KSC-STSM-14.1, Section 6.6.5. Personnel performing the handling function will be trained and certified to both NASA-KSC and contractor requirements. Emphasis will be placed on those practices required to preclude dropping.
- o Contractor personnel will utilize visual inspection methods prior to beginning any hazardous pressurized operation to re-verify system structural integrity. All pressure operations will comply with NASA-KSC-STSM-14.1, Section 6.6.2.
- o The helium spheres will be pressurized in the O and C Building. All operations near these spheres will be controlled via standard launch site safety practices which require that tools and other equipment be tethered to personnel to preclude dropping and impact damage.



- d. The KSC facility Helium Ground Pressurization System inadvertently over-pressurizes the airborne helium system. The airborne helium system ruptures, resulting in personnel injury via fragmentation. This hazard may be caused by any of the following:
- o The O and C Building Helium Ground Pressurization System does not provide for two levels of CFME over-pressure protection (pressure regulator/relief valve) and/or the O and C Building helium supply system relief is not sized to protect the airborne helium spheres in the event of a worst-condition failure of the nearest upstream regulator.
  - o The facility helium supply system plumbing presents a potential burst hazard due to a compromise in its factor-of-safety.
  - o Operational constraints (procedures) allow premature personnel access to pressurized systems.

Control of this hazard can be accomplished as follows:

- o The CFME project will coordinate the CFME helium system/KSC facility interface with KSC Engineering to assure that the relief system has sufficient flow and pressure capability to provide for satisfactory relief. Sizing will be based on failure of the nearest upstream pressure regulator.
- o The facility helium supply system plumbing is designed to provide a factor of safety when pressurized in accordance with those requirements stipulated in NASA-KSC-K-STSM-14.1, Sections 6.6.2 and 6.6.3. These requirements stipulate remote initial pressurization and the securing of flexible hoses to prevent flailing in the event of line failure.
- o The facility helium supply system must provide more than one level of protection to assure that the CFME airborne helium system is not overpressurized; these are:
  - 1) The KSC pressurization system pressure relief valve will not be set to greater than 10 percent above sphere loading pressure. Sphere loading pressure is 21600 kN/m<sup>2</sup> (3135 psia) (850°F)

- 2) The nearest upstream pressure regulator will be sized to CFME flow requirements.
- 3) Operational constraints preclude  $24100 \text{ kN/m}^2$  (3500 psig), which is below CFME helium sphere proof and burst pressure levels.

- e. A Nucleonic Gaging System with a KR-85 radioactive source is a potential candidate for the CFME, and has been identified as a potential hazard. If this gaging system is selected, details of hazard controls will be identified and documented.

None of the above hazards are of an uncontrollable or unacceptable nature. All will be resolved or verified by accepted safety procedures, tests, design analysis, or inspection and System Safety participation in critical test activities. All will be closed prior to the pre-delivery ground safety review.

## B. Flight Operations.

Flight operations include the nominal mission operations in addition to the anomalous mission and experiment aborts. Mission requirements and a representative operating sequence are discussed in the following paragraphs. A more detailed discussion of the flight operations is contained in the CFME Flight Plan, (Ref. 10).

1. Mission Requirements. A typical mission operating sequence for a seven-day mission is illustrated in Figure IV-4. The operation consists of a series of LH2 expulsions separated by static storage periods. During the expulsions, gas-free LH2 is delivered to flow instrumentation and vaporized, and then routed into the Orbiter vent system. Various operating modes are used for the expulsions, altering the thermodynamic state of the delivered liquid. Self-pressurized and helium-pressurized outflows are performed. Saturated and subcooled LH2 is expelled. Expulsion with the TVS and pressurization system inoperative is also performed. Data on the interaction and performance of the liquid acquisition device, TVS, and pressurization system will be obtained from these expulsions. During the storage periods, a constant tank pressure is maintained by the TVS.

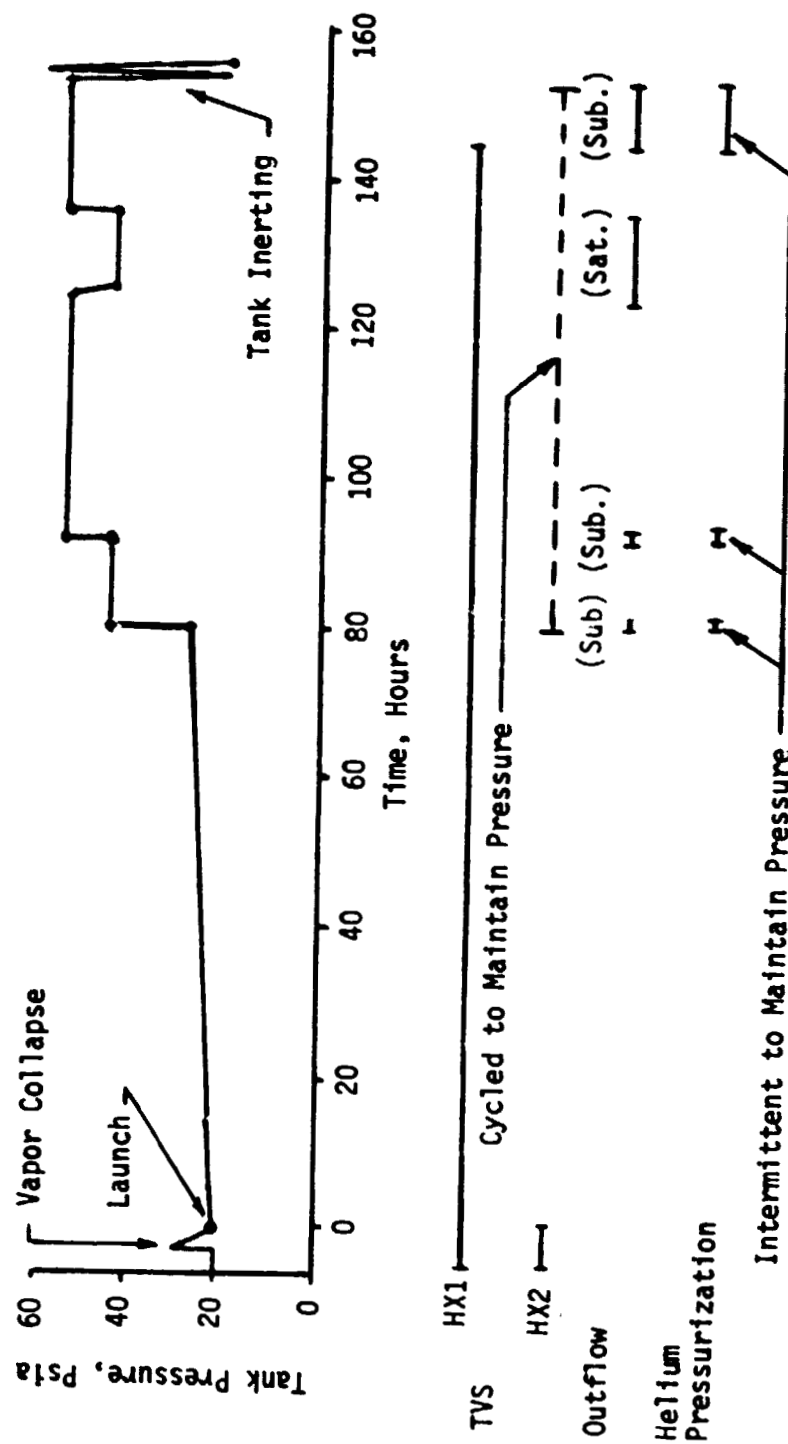


Figure IV-4 Typical Seven-Day Mission Timeline

Outflow and activation of the TVS and pressurization system are indicated by solid lines on Figure IV-4. Following a four-day storage and stabilization period, four LH2 outflow sequences are performed under varying conditions to demonstrate system capability.

2. Orbital Mission Operations. The flight timeline of the experiment is activated at liftoff (time zero), when the DACS EGSE is disconnected from the Orbiter at the T-0 umbilical. Operation of the DACS through the EGSE, and statusing of the experiment through the CRT of the EGSE, ceases at this time. The preprogrammed mission sequence clock contained within the DACS is activated at this time, and the DACS has full control of the mission sequence of events.

A positive indicator (e.g., talkback) is activated on the CFME Operations Control Panel in the Aft Flight Deck indicating that the DACS is initiating the normal mission sequence of events. The mission specialist merely notes that the experiment is operating in the normal clocked sequence and resets the indicator. This indication and check on normal experiment operation is a positive verification that the DACS has satisfactorily made the transition from ground-controlled operation to internal clock-controlled operation.

The data collected during the storage periods will permit evaluation of the performance of the thermal control system following the transient conditions of launch and at two tank pressure levels on orbit.

A stabilization period of approximately eighty (80) hours is provided to allow the thermal conditions within the tank to completely stabilize and to collect data on the TVS performance. The transient conditions introduced by launch acceleration, vibration, and thermal environment will have subsided, and a quiescent state will be established for the events that follow.

The TVS consists of two counterflow heat exchangers, HX1, designed to flow on a continuous basis, and HX2, designed to flow intermittently to control tank pressure. With HX1 activated, the pressure in the tank continues to rise (but not above a pre-set pressure of  $317 \text{ kN/m}^2$  (46 psia)). During this initial stabilization and storage period, the helium pressurization system remains inoperative.

Following the 80-hour stabilization period, the first outflow is performed. The helium pressurization set point is raised to  $310 \text{ kN/m}^2$  (45 psia), and the tank pressurized to this level. Liquid hydrogen will be delivered at a flow rate approximately equal to  $1.5 \text{ kg/h}$  ( $3.3 \text{ lb/hr}$ ). This flow rate will be established by a fixed orifice. The helium pressurization system will only be operated intermittently on an as-required basis to maintain tank pressure. If the combination of liquid outflow and flow through HX1 is not sufficient to maintain tank pressure, then HX2 will cycle to maintain pressure within  $7 \text{ kN/m}^2$  (1 psi).

After about 1.2 hours of outflow, the flow will be stopped, and the tank pressure maintained between  $310 \text{ kN/m}^2$  (45 psia) and  $317 \text{ kN/m}^2$  (46 psia). At 11 hours into this storage period, the setpoint of the TVS is changed to  $386 \text{ kN/m}^2$  (56 psia), the pressurization system is activated with a setpoint of  $379 \text{ kN/m}^2$  (55 psia), and the tank is pressurized with helium to  $386 \text{ kN/m}^2$  (55 psia). A  $7 \text{ kN/m}^2$  (1.0 psia) difference between TVS and pressurization setpoints is maintained to assure that vent and pressurization do not occur at the same time. Expulsion of subcooled LH2 is initiated with the pressurization system maintaining the tank pressure at  $379 \text{ kN/m}^2$  (55 psia). The LH2 has a vapor pressure of about  $310 \text{ kN/m}^2$  (45 psia) and the liquid temperature will essentially remain constant, giving a subcooling of  $0.94^\circ\text{K}$  ( $1.7^\circ\text{R}$ ) at the tank pressure. Expulsion at a flow rate of  $27.2 \text{ kg/hr}$  ( $60 \text{ lbm/hr}$ ) continues for 40 minutes.

A 33-hour storage period follows the second expulsion. The CFME returns to saturated LH2 outflow at this point. Saturated conditions are achieved by allowing blowdown to approximately  $310 \text{ kN/m}^2$  (45 psia) tank pressure. Because the previous outflow began with LH2 saturated at  $310 \text{ kN/m}^2$  (45 psia), the LH2 should be saturated at a somewhat greater pressure at this point. Since blowdown pressurization imposes the worst-case thermal conditions on the liquid acquisition device, this expulsion will establish if any two-phase flow will occur.

Before the third expulsion begins, the setpoint for operation of the TVS is changed to  $317 \text{ kN/m}^2$  (46 psia). Expulsion of subcooled LH2 is started, and blowdown of the tank pressure is permitted. Upon reaching  $317 \text{ kN/m}^2$  (46

psia), the flow rate is reduced and through the combination of outflow and the TVS operation, the tank pressure is maintained at that value. Outflow of the saturated LH2 continues for about 8 hours.

Following the third expulsion, the TVS setpoint is changed to  $386 \text{ kN/m}^2$  (56 psia) and the pressurization system is activated, raising the tank pressure back to  $379 \text{ kN/m}^2$  (55 psia). A final expulsion of subcooled LH2 is started and continues until tank depletion.

Depletion of the liquid acquisition device is usually associated with expulsion efficiency, as determined by the residual remaining when the first volume of pressurant gas enters the all-liquid region of the device. (The worst-case, on-orbit vectorial orientation would have the screen breakdown location at depletion over the tank outlet so that pressurant passing into the acquisition device would immediately enter the tank outlet). Depletion of the tank obviously does not occur at the same time because there is a volume of liquid remaining within the acquisition device at breakdown, and there is also a small volume of liquid (on the order of 0.1 percent or less) still retained within the bulk fluid region of the tank.

Pressurized outflow of the tank will continue, sweeping liquid hydrogen from the acquisition device as two-phase flow with the entrained pressurant. The relatively warm helium pressurant flowing through the wetted screen will cause screen dryout induced by vaporization. At this point, when the majority of the liquid within the device has been expelled through the outlet, the retention capability of the acquisition device is lost. The only significant quantity of liquid remaining within the tank is the residual liquid buildup within the fillet pockets of the structure.

The tank is now subjected to the inerting process of alternately pressurizing with relatively warm helium and blowing-down the tank to vacuum through the tank outlet. After three purge cycles, the remaining quantity of hydrogen within the tank is sufficiently reduced so that the tank can be locked up and the pressure resulting from warmup will not exceed the maximum pressure limit of  $413 \text{ kN/m}^2$  (60 psia). Part of the inerting process will be for the DACS to open valve V9 to make the helium in the isolated helium sphere available for use.

Pressure levels in all spheres will thus be reduced to minimum levels for landing. Normal operating procedure, however, is to leave the tank outflow line open to vacuum following the last purge cycle until just prior to final safing and shutdown of all payload operations. This will assure the least amount of hydrogen at the largest possible temperature before lock-up. A small amount of helium will be injected into the tank to a prescribed pressure level (several psi) for reentry and landing. Since the storage tank is designed to withstand a vacuum condition, careful monitoring and control to the low specified pressure level in the tank prior to reentry into the atmosphere is not required.

3. Mission Abort. Numerous backup operational modes programmed into the DACS, and a series of indicator talkbacks and switches located on the CFME Operations Control Panel in the Aft Flight Deck have been defined to handle expulsion and inerting of the experiment when mission abort circumstances arise. The decision of how the LH2 tank should be conditioned for each possible Orbiter abort mode is dictated to a large extent by the time available to accomplish the necessary operations. The abort outflow rate of the tank is 81.6 kg/hr (180 lb/hr). At this outflow rate, the tank can be emptied of liquid in a half-hour. This does not include any inerting with helium. The standard on-orbit inerting operation takes approximately one-hour. This multiple purge sequence and duration is driven by the desire to condition the tank so that it can be locked up without the resulting pressure level exceeding the  $413 \text{ kN/m}^2$  (60 psia) limit (as discussed in the previous section). An alternate quick purging operation is available for abort operations to remove as much hydrogen as possible from the tank. This involves blowing down the pressurization spheres in a continuous flow mode through the hydrogen tank.

In general, time and GSE facilities are available on the pad to handle prelaunch abort conditions. If the Orbiter enters a Return-to-Launch-Site (RTLS) abort situation early in the mission, during liftoff and/or ascent, there is not sufficient time to empty and inert the tank, and the Orbiter will return with a loaded tank. Offloading will occur either on or near the runway with portable GSE, or in the OPF. If the Orbiter enters an Abort-Once-Around (AOA), there will be sufficient time to empty the tank. However, the inerting will be somewhat different than that performed during a normal mission

sequence. If an abort condition arises during the orbital mission phase, the tank can be emptied of liquid and inerted prior to entry. Each of these mission abort sequences is discussed in the following paragraphs. Automatic operations associated with an experiment abort, and the built-in, backup operational capability that exists through the Operations Control Panel in the Aft Flight Deck are discussed.

4. On-Orbit Abort. The liquid hydrogen tank can be depleted and inerted if a mission abort occurs after the Shuttle has achieved orbit. Initiation of the abort sequence for tank outflow is accomplished by activating the abort switch on the Operation Control Panel in the Aft Flight Deck. Closing the switch signals the DACS to transfer to the programmed abort sequence. The pressurization system is activated to establish  $379 \text{ kN/m}^2$  (55 psia) in the tank. Valves V6 and V8 (or V6A and V8A if the DACS receives a signal that either V6 or V8 is not functioning) are cycled in a bang-bang operation until the required pressure level is obtained. Valves V1A and V3A are then opened to commence outflow at the abort flowrate of 81.6 kg/hr (180 lb/hr). The R3A orifice is sized to control the flowrate to this level. The pressurization valves continue to cycle, maintaining tank pressure at  $379 \text{ kN/m}^2$  (55 psia).

When tank depletion occurs, as indicated by the two temperature measurements in the outflow line, tank inerting is initiated. Two inerting sequences are possible. The automatic inerting sequence that is used at the termination of a normal mission will be programmed into the abort and inert operating mode. As previously described, this consists of a series of three pressurization and vent cycles. The total abort and inerting operation in the fully automatic mode will take approximately 1-1/2 hours assuming a nearly full tank.

If it is required to inert the tank more rapidly, activating the helium backup switch on the Operation Control Panel will simultaneously open valves V6A and V8A. This will expel all the helium in the three non-isolated spheres through the tank and out the outlet line. Orifice R8 is sized to control the liquid flowrate to 81.6 kg/hr (180 lb/hr). When both pressurization valves are open, the filter and valves limit the helium flowrate to about .036 kg/sec



(0.08 lb/sec). Thus the operator-controlled inerting can be accomplished on the order of several minutes. The tank, however, cannot be locked-up at this point without exceeding the  $413 \text{ kN/m}^2$  (60 psia) limit.

5. CFME Experiment Abort. If an experiment anomaly occurs, two crew alert talkbacks on the CFME Operation Control Panel indicate that the experiment is no longer in the normal, programmed operating mode. These talkbacks are the V11/V14 open, indicating pressure is being relieved by venting helium and/or hydrogen from the pressure vessel, and the tank pressure low, indicating system pressure has dropped below  $103 \text{ kN/m}^2$  (15 psia). A discussion of the operation of these two indicators is presented below.

- a) Relief valve V11/V14 is open, and the system is relieving pressure. (Valves V11/V14 are controlled by the DACS and open when the  $413 \text{ kN/m}^2$  (60 psia) pressure limit is reached). Helium and/or hydrogen is dumped thru the Orbiter vent. No action is required by the mission specialist. The talkback merely indicates that the tank is automatically discharging fluid to maintain  $413 \text{ kN/m}^2$  (60 psia). The talkback comes on and stays on, indicating that either valve V11 or V14 has opened.

The reset switch will restatus the V11/V14 valve position; if either is open, the talkback will again come on. With this type of automatic pressure control using the DACS, any time the pressure wants to exceed  $413 \text{ kN/m}^2$  (60 psia) valve V11/V14 opens. As long as the pressure rise time does not exceed the combined DACS and valve response time, the burst disc will not blow. If the DACS is non-operative, valve V11/V14 cannot be opened, and if the pressure set point for the burst disc is reached, the burst disc will blow.

- b) Pressure in the tank drops below  $103 \text{ kN/m}^2$  (15 psia). Each time the DACS cycles through the instrumentation signals, it checks the tank pressure. A talkback indication on the panel signals that the pressure is below the initial loaded pressure of  $103 \text{ kN/m}^2$  (15 psia). If talkback V11/V14 is also on, then there is a high possibility that the burst disc has blown. If talkback V11/V14 is not on, then there is a high probability of a leak from the tank

assembly. The leak may be through the valves and into either the T-0 or Orbiter vent systems, it may be into the payload bay around the experiment, or it may be into the vacuum jacket, in which case the pump-out/relief valve relieves pressure, dumping hydrogen through the vent line.

For the latter case if the Orbiter is still on the pad, the EGSE is used to assess the condition. Nitrogen purge of the payload bay helps to disperse the hydrogen. (Note: While on the pad, a simultaneous indication of low pressure is transmitted to the EGSE CRT display and the Aft Flight Deck. Thus, if the Flight Crew has not yet entered the Orbiter, the ground crew will still receive an alert indication that a problem exists). The display and operational control capability of the EGSE permits off-loading and inerting of the experiment, if required.

If the RV11/RV14 talkback is not on and the Orbiter is on-orbit, then the leaking hydrogen is dispersed to vacuum. When a convenient time in the mission is reached (e.g., when operation of another experiment will not be adversely impacted by an increased discharge of hydrogen), the abort and horizontal drain switches are activated. This allows blowdown expulsion and boil-off of liquid from the tank until the tank pressure has decreased to near-vacuum conditions.

The DACS can be inoperative for two reasons: Power to the DACS is cut-off or the DACS system malfunctions internally. The only indication that the DACS is down is that the mission specialist gets a signal that Spacelab is no longer supplying power to the payloads. If the DACS malfunctions internally, no signal is provided to the mission specialist. In either case, the thermodynamic vent system valves could be locked in the closed position and tank pressure would then continue to rise. For the case where the DACS loses power and power is not restored within 60 minutes, the mission specialist switches the Abort and Backup, and Helium Backup switches in that order, and the tank is emptied of liquid prior to the burst disc blowing. (The burst disc still provides a backup, but the preferred approach is to empty the tank under controlled conditions rather than having the burst disc blow). The

Abort, Helium and Horizontal Drain switches on the OCP are wired separately to Shuttle power, in addition to being wired to the DACS, so that they can be operated independently by the Mission Specialist, if required.

If the DACS malfunctions internally, pressure could continue to rise until the burst disc blows. Eventually, the low pressure talkback may come on, in which case the Abort and Horizontal Drain switches are activated. This allows blowdown expulsion and boil-off of liquid from the tank until the tank pressure has decreased to near-vacuum conditions. An indication that a DACS malfunction was responsible for the experiment abort will be obvious from analysis of the data on the tape recorder. If the low pressure talkback does not come on, the mission specialist still has one way of discerning the DACS malfunction so he can activate the two switches initiating blowdown outflow. The mission sequence indicator will not have advanced as the mission progressed. A check of this indicator near the end of the mission will provide a check on DACS functioning and allow dumping of fluid using the two switches on the OCP. In all mission situations, including a normal mission per the programmed mission sequence, the Mission Specialist activates the Abort and Helium switches prior to entry to remove liquid and assure the tank is inerted.

If both pressurant valves, V6 and V8, or alternately V6A and V8A, should fail open, then the DACS will immediately open the outlet valves, V1A and V1B. The orifice, R6, in the pressurization line will limit the flow such that pressure in the tank will not exceed  $413 \text{ kN/m}^2$  (60 psia). Operation of valve V9 is controlled by DACS software and will be opened when supplemental pressure is required based on the operating mode of the experiment.

If the DACS loses power, but is repowered within 60 minutes, then the following procedure is followed to assure that the programmed mission in the DACS software is transferred to the proper location. Normally, as power returns to the DACS, the software will reset the experiment clock to zero and start the mission timeline all over again. (The circuit breaker on the CFME OCP may need to be reset following the power-down). The DACS will send a signal to the Mission Sequence Indicator, indicating that it has been powered-up.

The Mission Specialist then restarts and transfers the experiment to the proper mission mode using the Mission Sequencer on the OCP. Mission Sequence Instructions supplied with the OCP will be used to establish the operating procedure for the Mission Sequencer and Mission Sequence Indicator. Basically, a table of mission elapsed time and experiment timeline modes will be used. The experiment timeline will be divided into 7 time periods and, based upon the mission elapsed time, the Mission Specialist will sequence the software to the beginning of the next experiment time period.

A chart indicating how malfunctions and/or aborts are handled automatically and by the Mission Specialist using the CFME Operation Control Panel, is presented in Figure IV-5. The on-orbit operations presented in Figure IV-5 are referenced from the time of lift-off. In all cases of experiment malfunction or Orbiter abort, the CFME is designed with an automatic vent capability and a burst-disc backup to relieve tank pressure should the need arise.

6. Safety. Currently there are six potential hazards identified in Attachment II of the Flight Safety Compliance Data Package (CFME-79-23, Ref. 11), dated August 27, 1979, which are not duplicated by those already discussed. They are all associated with airborne CFME systems including hazard causes and hazard controls. The Phase I Flight Safety Review was prepared to be in compliance with the 1976 Draft Safety Policy and Requirements (SP and R) document (Ref. 12) since the NHB 1700.7 document (Ref. 4) had not been released at that time. The following hazard causes and controls will need to be updated to the NHB 1700.7 requirements prior to the Phase II Flight Safety Review. The potential hazard causes and controls are summarized below:

- a. During Orbiter flight the liquid hydrogen vessel leaks, causing hydrogen to spray into the Orbiter cargo bay. Optical surfaces on associated experiments and/or nearby reflective panels could become contaminated. Personnel toxicity or fire hazard is possible at the landing site when an atmosphere which supports combustion is present. This hazard may be caused by any of the following:

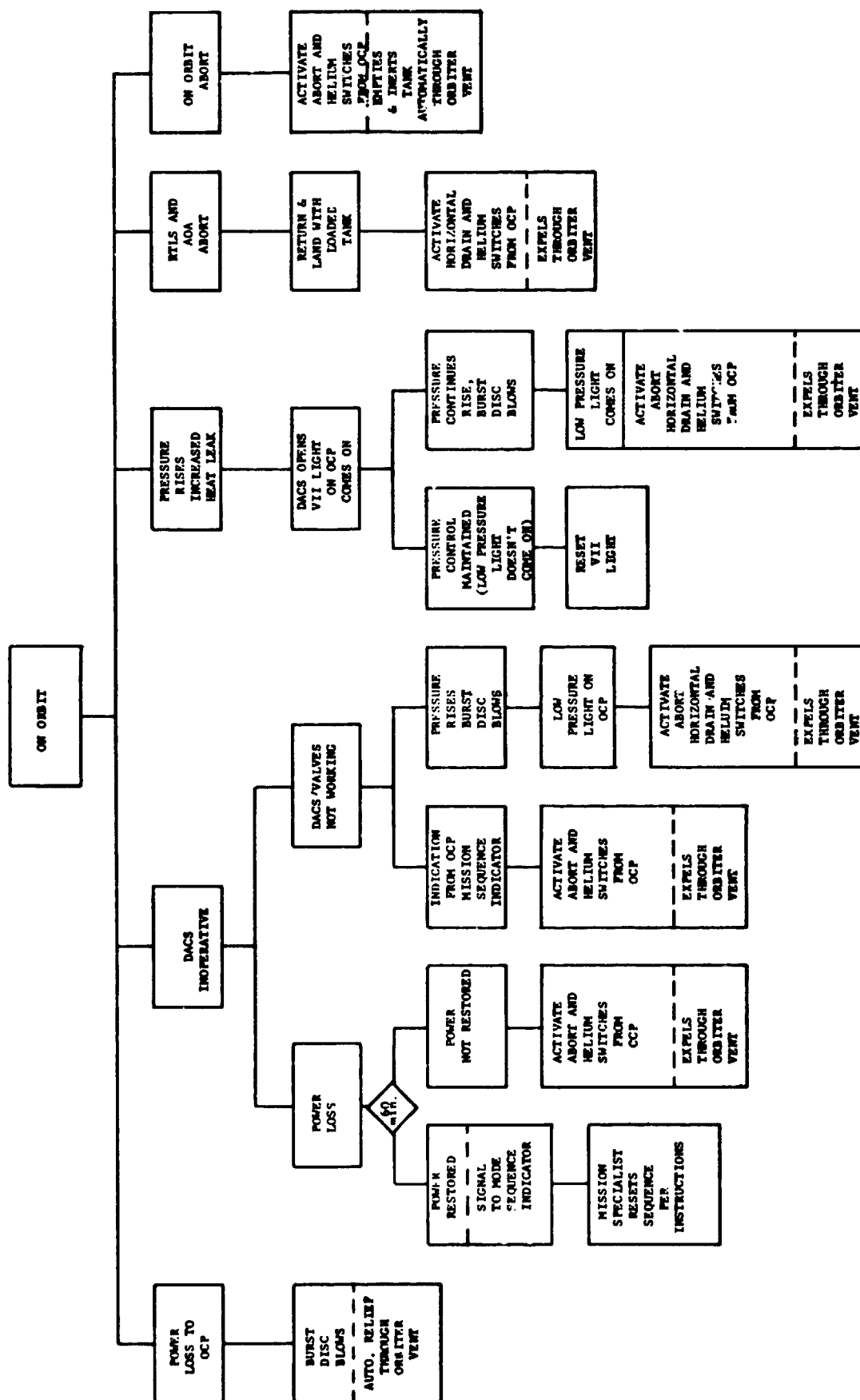


Figure IV-5 On-Orbit Abort and Malfunction Decision Chart

- o Material defects, off-nominal workmanship and/or undetected damage to the liquid hydrogen vessel exists following fabrication and test.
- o The liquid hydrogen vessel is exposed to out-of-limit pressurant supply, temperature and/or boil-off.
- o Vessel factor-of-safety is diminished, and leak(s) occur.

Control of this hazard may be accomplished as follows:

- o Contractor material control, Manufacturing process plans, Quality inspection points, test procedures and handling provisions will assure that the hazard presents a no-risk condition.
- o The liquid hydrogen vessel is protected via pressure relief to preclude overpressurization from any source. These provisions satisfy SP and R requirements of paragraphs 5.1.1 and 5.1.2 for fail-safe design and single-point failures, and provide the required control for the hazard.
- o The liquid hydrogen vessel will be designed to "leak before burst" as stipulated in MIL-STD-1522, Section 4.4(a). This provision allows for a potentially non-hazardous function and satisfies paragraphs 5.1.6 and 5.1.20 of the SP and R as it pertains to structural and pressure vessel design.
- o The liquid hydrogen vessel will be designed to contain hazardous fluids under all STS environments and will incorporate factors-of-safety (3.75 at room temperature and 6.44 at LH<sub>2</sub> temperature) which are greater than those required by SP and R paragraphs 5.1.6 and 5.1.20 for pressure vessel structure.
- o The liquid hydrogen vessel will be tested in accordance with the testing requirements specified in MIL-STD-1522, Section 4.0. Section 4.3, Table I, stipulates that only pressure vessels which operate above 500 psig be proven via the use of three test items. The CFME liquid hydrogen vessel operates below this value; accordingly this requirement is not applicable. Compliance with the testing activities stipulated in MIL-STD-1522 satisfies the verification requirements in paragraph 5.1.24 of the SP and R.

- o The liquid hydrogen burst disc/relief valve is protected from helium pressurant surges (pressure spikes) via a line orifice to prevent inadvertent hydrogen relief system activation. System test activities will demonstrate that no worst-case spike can cause relief system operation.
- b. During Orbiter/CFME mission operations, the liquid hydrogen system ruptures/collapses, causing a release of liquid hydrogen into the cargo bay. Fire and/or explosion is possible in the presence of ignition sources and/or an atmosphere which supports combustion. This hazard may be caused by any of the following:
- o Structural failure via stress corrosion, temperature extremes, undetected damage or material defects.
  - o Structural failure due to dynamic loads and/or environmental conditions imposed via Orbiter mission operations.
  - o The liquid hydrogen vessel and system fails to contain under all Orbiter operating regimes.
  - o Vent/relief system fails. Liquid hydrogen vessel and/or associated system ruptures due to hydrogen boil-off.
  - o Venting liquid hydrogen into a common Orbiter vent line (used to vent other commodities) could create combustion.
  - o Liquid hydrogen leaks into vacuum jacket and pressure increases due to flash-off.

Control of this hazard may be accomplished as follows:

- o The CFME liquid hydrogen system (and the entire experiment) will be designed to avoid failure from any source, including stress corrosion (SP and R paragraph 5.1.18).
- o The liquid hydrogen vessel and associated system (including vacuum jacket) will be designed to withstand all STS environments without failure or loss of containment. These

environments will include those dynamic loads transmitted to the CFME liquid hydrogen vessel as a function of the tank assembly mounting to the Spacelab pallet. The CFME test program will be keyed to all STS environments, including vibration and temperature. The CFME testing program will meet the intent of SP and R paragraph 5.1.24 (test to expected operating regimes) and the design will satisfy SP and R paragraphs 5.1.6.1.14, 5.1.20 and 5.1.21.

- o The liquid hydrogen vent and relief system will be designed so it cannot fail to operate, if needed. In all cases the liquid hydrogen system in combination with the vent and relief system shall maintain containment via the system factor-of-safety and the experiment dump capability through the Orbiter overboard vent. (Experiment vent requirements will be negotiated with the STS Operator, as required.)
  - o The CFME project will evaluate the impact of venting liquid hydrogen into the Orbiter vent with other Orbiter fluids, and reflect a firm configuration by the Phase II Safety Compliance Review.
  - o Vent relief capability is planned for the vacuum jacket. If the relief valve is activated, the hydrogen vapor passing through the valve will be ducted to the Orbiter vent line.
- c. The liquid hydrogen system or its interfaces with the Fuel Cell Servicing System (FCSS) does not contain and leaks occur which result in a liquid hydrogen spill. Personnel may be exposed to frost burn or toxicity hazard. Equipment damage via fire or contamination is possible. This hazard may be caused by either of the following:
  - o The CFME liquid hydrogen system experiences undetected damage and the factor-of-safety becomes compromised.
  - o Hazardous operations are not identified and controlled.

Control of this hazard may be accomplished as follows:



- o The design will be in compliance with SP and R paragraphs 5.1.4, 5.1.20 and 5.1.21 relative to design for containment and factors-of-safety. These factors-of-safety compensate for minor system damage or degradation.
  - o All hazardous operations for the CFME will be identified prior to experiment delivery and all procedures controlling hazardous operations will be stamped accordingly. This hazard control will comply with SP and R paragraph 5.1.26.
  - o Prior to shipment of the CFME to the launch site, the total system will have successfully completed proof and leak tests.
- d. Electrical system becomes overloaded and/or extreme temperature conditions cause degradation of wire insulation. Short circuiting and/or arcing occurs with potential burning of wire insulation and/or fire/explosion if an explosive atmosphere exists. This hazard may be caused by any of the following:
- o The CFME does not incorporate intrinsic overload protection.
  - o Wire insulation is not compatible with all STS environments.
  - o CFME leaks into the cargo bay and explosive vapors become concentrated.

Control of this hazard may be accomplished as follows:

- o The CFME electrical design provides for a 20 Amp. circuit breaker on the CFME Operations Control Panel located on the Orbiter Aft Flight Deck. This provision complies with SP and R paragraph 5.1.12 for electrical system protection.
- o All wire insulation (and other materials) used on the CFME will comply with the intent of SP and R paragraph 5.1.15 for the control of flammable materials. The CFME Project will utilize NASA approved materials lists in the identification of experiment materials. This activity is the subject of on-going Safety surveillance.

- o The CFME is controlled by the DACS and operated via the electrical system (with the exception of the mechanically actuated relief devices). The current CFME System Design has no one single failure point other than fail-safe even if the control valves "fail as is" on loss of power. Also, the CFME provides for an independent means of opening outflow valves V1A and V3A to maintain a liquid hydrogen outflow capability should the need exist. Additionally, the liquid hydrogen vessel relief system (mechanically actuated) will relieve, if needed.
  - o The CFME will be designed to comply with SP and R paragraph 5.1.4 on hazard detection/safing without requiring an interface with the Orbiter Caution and Warning System. The rationale for this design approach is automatic corrective action. A brief scenario for this approach is:
    - 1) Vent valves V4A, V4B, V5A and V5B maintain the system at normal operating pressure.
    - 2) If the DACS/electrical system fails, the vent valves will not maintain normal hydrogen vessel pressure. The burst disc (BD11) opens (413 to 483 kN/m<sup>2</sup> – 60 to 70 psig) and system outflow valves V1A and V3A are opened by independent electrical command from the OCP. Hydrogen outflow occurs.
  - o The experiment will be controlled by the mission specialist through the CFME Operation Control Panel. Two crew alert talkbacks are used to indicate that the experiment is no longer in the normal programmed operating mode.
- e. Material off-gassing in the crew habitable area presents a crew toxicological hazard. Material off-gassing in the cargo bay in combination with an ignition source presents a fire hazard. Contamination of optical surfaces and solar arrays is also possible.
- o This hazard may be caused by insufficient control of materials identified for use.

- o It may be controlled by insuring that all CFME materials will be in compliance with NASA approved materials listings and will be a subject of on-going CFME Project control at the design level. This hazard control will meet the intent of SP and R paragraphs 5.1.15, 5.1.16 and 5.1.17.
- f. The experiment helium supply spheres experience rupture due to temperature extremes and/or the experiment attach fittings do not maintain structural integrity under landing loads. Crew injury results via impact damage and/or hydrogen fire. This hazard may be caused by the following:
  - o The experiment, including its pressure vessels and attach points, cannot withstand Orbiter impact (Return-to-Launch-Site-Abort). The experiment hydrogen and helium pressurization systems do not meet STS containment requirements during landing.

Control of this hazard may be accomplished as follows:

- o The CFME and its attach points to the Spacelab pallet will incorporate a structural factor-of-safety of 1.40 for general structure (normal mission phases) and incorporate a similar factor-of-safety for a 4.5-G longitudinal load. Structural testing will consider all Orbiter flight regimes. This hazard control will comply with SP and R paragraphs 5.1.6, 5.1.7 and 5.1.24.

None of the above hazards are of an uncontrollable or unacceptable nature. All will be resolved or verified by accepted safety procedures, tests, design analysis, or inspections, and will be closed prior to the pre-delivery flight safety review.

## V. EXPERIMENT ANALYSIS

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Detailed hydrodynamic, thermal, and structural analyses were performed in support of the CFME design. These analyses, presented in References 19 through 21, are summarized in this Chapter.

### A. Hydrodynamic Analysis.

This section presents the hydrodynamic analysis performed for the CFME. The analysis concerns the design of the liquid acquisition device and the plumbing. The hydrodynamic analysis of the plumbing was concerned primarily with establishing the schematic layout of the lines, and determining the requirements for the system components and line sizes. The liquid acquisition device must be capable of expelling gas-free liquid hydrogen from the tank, in the Spacelab on-orbit operating environment. In addition to expelling at the maximum normal flow rate of 27 kg/hr (60 lbm/hr), the device must be capable of emptying the tank in approximately 30 minutes at 81.6 kg/hr (180 lbm/hr). An expulsion efficiency of at least 98 percent is desired.

The plumbing consists of the following elements:

Outflow Line - This line carries the liquid hydrogen from the liquid acquisition device through the flow instrumentation to the Orbiter vent system.

Pressurization and Vent Lines - These lines provide for the regulation of helium pressurant for the tank and venting of the tank through either the ground or airborne vent line.

Thermodynamic Vent Lines - These lines consist of two heat exchangers, using liquid hydrogen drawn from the outlet line as a refrigerant, that are attached to the vapor-cooled shield.

Fill and Drain Line - Ground filling of the tank and draining while the Orbiter is in the vertical attitude is performed through this line.

Horizontal Drain Line - Draining of the tank, while on the ground and with the Orbiter in the horizontal attitude, is performed through this line.

1. Liquid Acquisition Device. The device configuration was shown in Figure III-5. It has four channels manifolded at the outlet. The side of the channel facing the tank wall is covered with screen, but the screen is truncated near the top of the tank, terminating the flow passage. The sheet metal continues so the four channels join at the top of the tank. The screen is truncated to prevent exposure of the screen to the ullage during the launch phase of the mission. A ten percent ullage level was selected for the truncation level, considering propellant vent loss during launch hold and slosh during boost. The height of a ten percent ullage in a 106-cm (41.7-in) diameter tank is 20.8-cm (8.2-in), which is the point of truncation.

Dutch-twill screen, 325 x 2300 mesh, was selected because of its high retention capability, acceptable wicking capability, and proven fabricability. The retention capability ( $\Delta P_c$ ) is  $0.30 \text{ kN/m}^2$  (0.044 psi) for liquid hydrogen saturated at  $380 \text{ kN/m}^2$  (55 psia),  $25.7^\circ\text{K}$  ( $46.2^\circ\text{R}$ ). As the saturation pressure decreases,  $\Delta P_c$  increases. Therefore, this is a worst case condition.

The residual liquid in the tank, at the point of screen breakdown was estimated. The liquid will be oriented about the device, rather than form isolated puddles between channels. The total residual liquid volume is  $3950 \text{ cm}^3$  ( $241 \text{ in}^3$ ) which is 0.6 percent of the tank volume, indicating that the requirement of less than 2 percent residual is easily satisfied. This residual was obtained by adding the volume of liquid within the flow channels to the liquid fillets around the sheet metal and between the screen surface and the tank wall at the point of first ullage bubble ingestion through the screen into the flow channels.

2. Outflow Line. A complete schematic of the CFME plumbing was shown in Figure III-1. A summary of the hydrodynamic analysis for each of these lines is given in Table V-1. Also, a simplified schematic of just the outflow line portion of the CFME is shown in Figure V-1.

The abort outflow is routed around the flowmeter to avoid over-ranging the flowmeter and its large flow restriction. The orifice is placed upstream of the valve to regulate the liquid flow. Flashing of the hydrogen will occur

Table V-1 CFME Hydrodynamic Analysis Summary

Line	Maximum Flowrate		Line Diameter	
	kg/hr	(lbm/hr)	cm	(in)
Outflow	82	(180)	1.3	(0.5)
- Abort Outflow	82	(180)	1.3	(0.5)
- Mission Outflow	27	( 60)	1.3	(0.5)
Pressurization	1.9	(4.3)	0.64	(0.25)
Vertical Vent	52	(116)	1.3	(0.5)
Pressurization/Vent	52	(116)	1.3	(0.5)
Horizontal Vent	52	(116)	1.3	(0.5)
Fill and Drain	154	(339)	1.3	(0.5)
Horizontal Drain	82	(180)	1.3	(0.5)
Thermodynamic Vent HX1	0.02	(0.05)	0.48	(0.19)
Thermodynamic Vent HX2	0.08	(0.175)	0.48	(0.19)

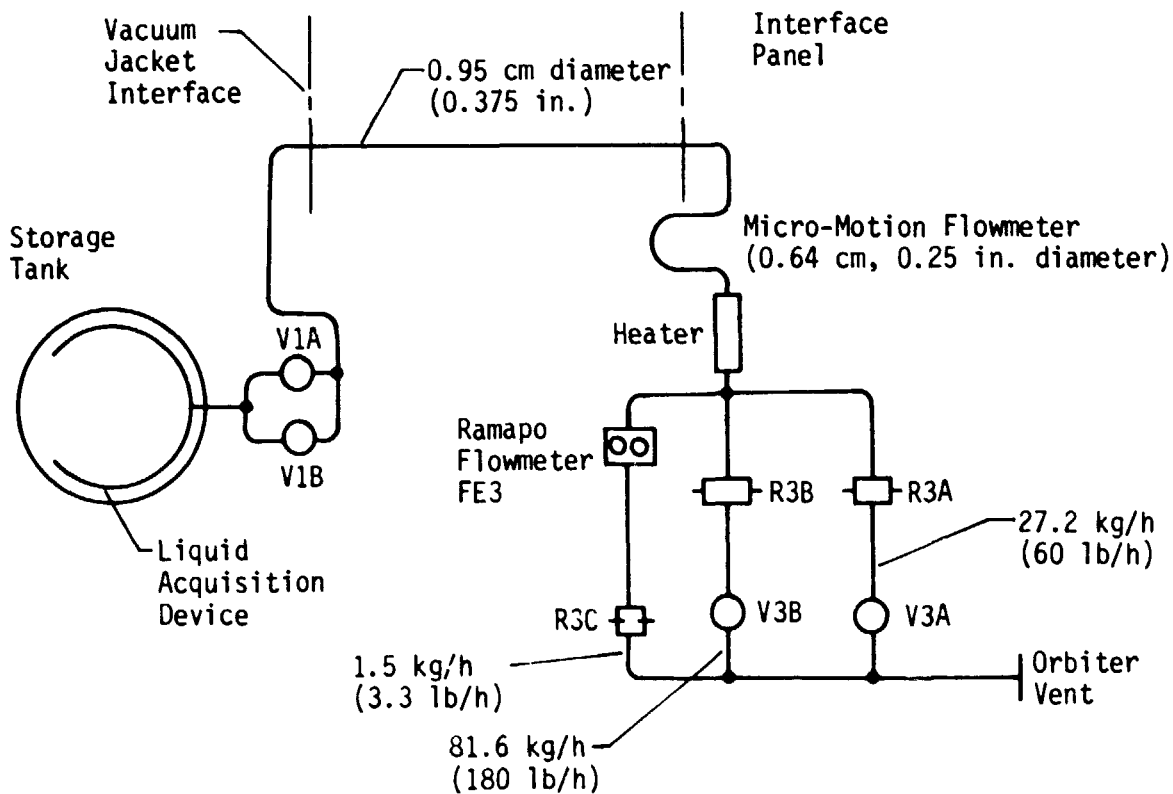


Figure V-1 Outflow Line Schematic

downstream of the orifice. A 1.3-cm (0.5-in) line and valve is used in this portion of the outflow line.

3. Pressurization and Vent Lines. The pressurization and vent portion of the plumbing is shown in Figure V-2. Pressurant regulation is accomplished with two series valves. The first valve is opened, admitting the high pressure helium to the volume between the valves. After closing the first valve, the second valve is opened, allowing blow-down of the volume between valves into the storage tank. A redundant pair of valves is provided so that either leg can be used. By monitoring the valve position indicators, a leg with a valve failed open or a valve that fails to open can be detected and the other leg can be used.

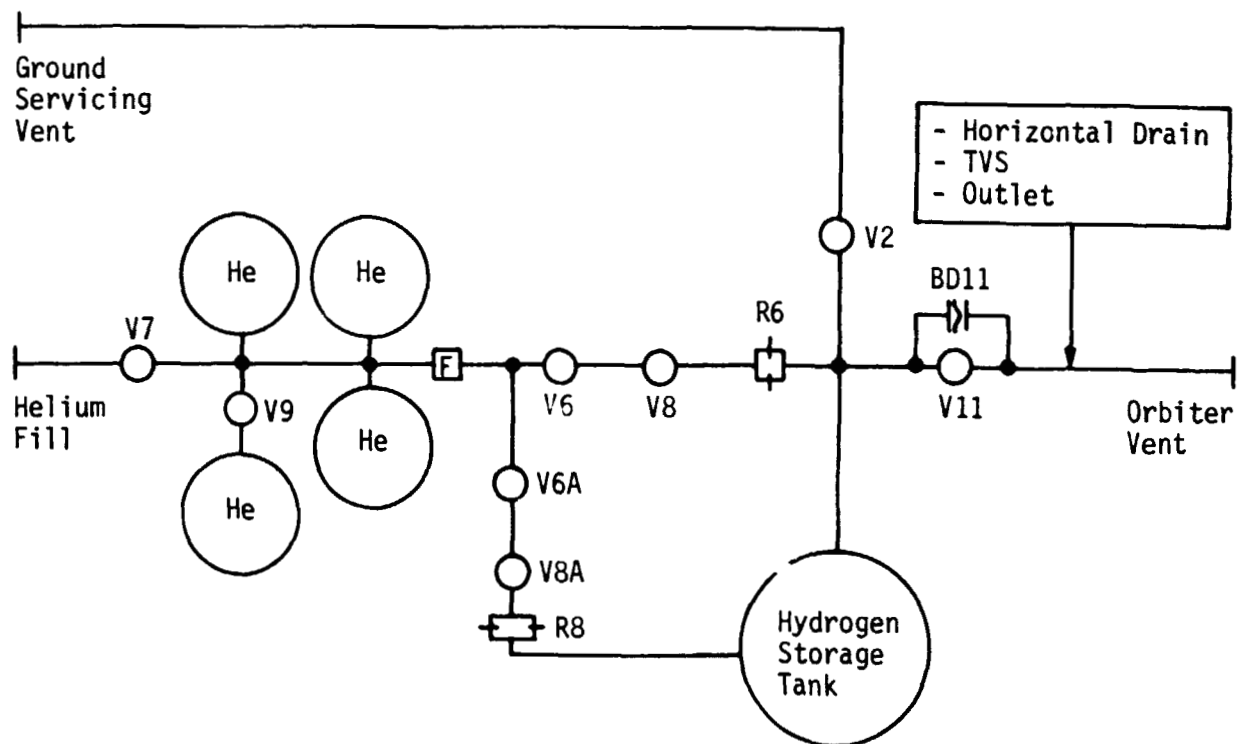


Figure V-2 Pressurization and Vent Line Schematic

The volume between the two valves was selected as 16 cm<sup>3</sup> (1.0 in<sup>3</sup>). A 15-cm (6.0-in) length of 1.3-cm (0.5-in) diameter tubing provides this volume. The mass of helium in this volume, after opening the first valve is

$$M = \rho V = 2.9 \times 10^{-4} \text{ kg } (6.4 \times 10^{-4} \text{ lbm})$$

using a minimum helium density based on a storage pressure of 14000 kN/m<sup>2</sup> (2000 psia) and temperature of 390°K (710°R). The mass is 1.4 x 10<sup>-3</sup> kg (3.0 x 10<sup>-3</sup> lbm) at 21000 kN/m<sup>2</sup> (3000 psia) and 120°K (220°R).

For the case where the larger pressurant mass, calculated above, is added to a minimum ullage volume of 5 percent, at 380 kN/m<sup>2</sup> (55 psia) and 53°K (95°R) (maximum temperature from the pressurization analysis), the tank pressure increase from a single pulse is 5 kN/m<sup>2</sup> (0.7 psi). Lines and valves of 0.64-cm (0.25-in) diameter are adequate for the pressurization plumbing.

There are two vent lines, both using 1.3-cm (0.5-in) diameter lines and valves. The ground servicing vent is used during tank loading and topping, and to reduce the tank pressure during ground hold should it become necessary. The airborne vent line is used from launch through completion of the mission for emergency pressure relief and tank inerting. The burst disk in the airborne vent line permits pressure relief should either vent valve fail to open. The following conditions were evaluated in sizing the vent system components:

- 1) air leak into vacuum jacket;
- 2) hydrogen leak into vacuum jacket;
- 3) helium leak into vacuum jacket; and,
- 4) venting of liquid hydrogen due to its orientation over the vent in low-g.

4. Thermodynamic Vent Lines. The plumbing of the thermodynamic vent is shown in Figure V-3. The lines are 0.48-cm (0.19-in) diameter. All the valves have an equivalent sharp-edged orifice diameter of 1.3-mm (0.05-in) with a C<sub>D</sub> of 0.65. The Viscojets produce a relatively large pressure drop at the inlet to



the thermodynamic vent. As part of the thermal analysis, it was established that the conditions downstream of the Viscojets would cover the following range:

$$\dot{m} = 0.02 \text{ to } 0.08 \text{ kg/hr (0.05 to 0.175 lbm/hr)}$$

$$P = 34 \text{ to } 138 \text{ kN/m}^2 \text{ (5.0 to 20 psia)}$$

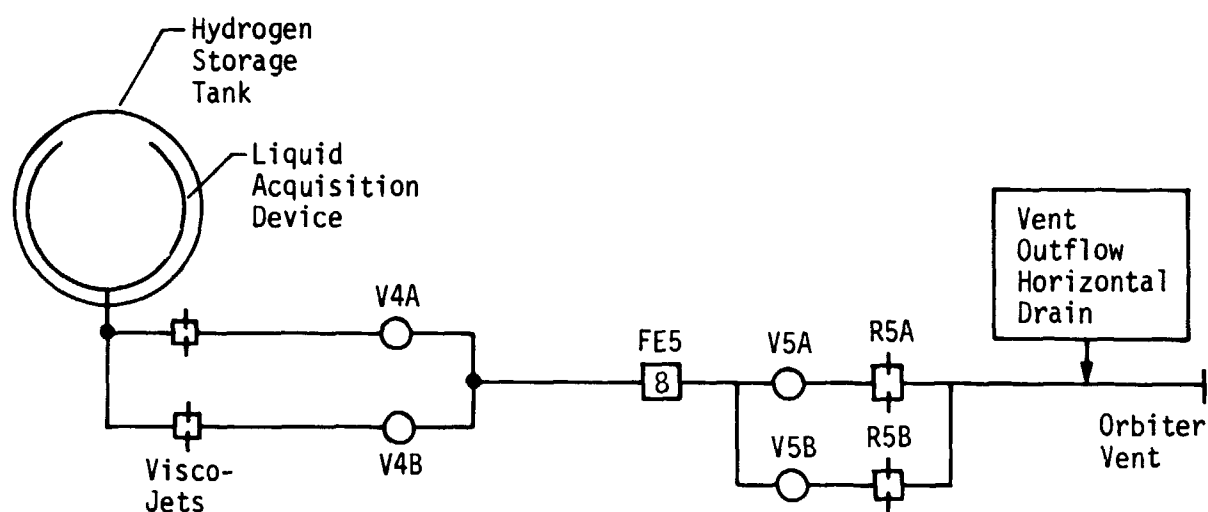


Figure V-3 Thermodynamic Vent System Schematic

5. Fill/Drain and Horizontal Drain Lines. Neither of these lines pose any significant hydrodynamic problems. Lines and valves of 1.3-cm (0.5-in) diameter were selected for both.

## B. Thermal Analysis.

This section presents a summary of the thermal analysis conducted on the CFME CDR design configuration. Additional details of the analysis are contained in the Thermal Analysis Report (Reference 20). The Cryogenic Storage Analysis Model (CSAM) is briefly described, followed by a summary of the storage tank assembly thermal analysis and the CFME payload thermal analysis. The latter analysis presents a preliminary evaluation of the effect on the experiment design of the on-orbit thermal environment to which the external surfaces of the entire payload are exposed.

1. Cryogenic Storage Analysis Model. The principal tool used for both the transient and steady-state thermal analyses of the CFME was the Cryogenic Storage Analysis Model (CSAM). This comprehensive computer program includes a transient heat transfer network analysis, an internal tank thermodynamics analysis, and a heat exchanger analysis for simulation of the thermodynamic vent system. User-oriented input routines provide flexibility in describing the model, and configurations are completely determined from input data. Events and boundary conditions are programmable, permitting simulation of an entire mission with a single input. A general computer logic flow diagram for CSAM is shown in Figure V-4.

A heat transfer network, input to the computer model, is analyzed in a manner that simulates the transient phenomena which physically occur. In order to perform such a complex numerical solution to the partial differential equation for unsteady state conduction, a common simplifying assumption is made. Each portion of a heat transfer network is defined as a point-source, or node. A node is given a mass corresponding to the portion of the system it represents, as well as an entire set of material and thermal properties. This assumption reduces a three-dimensional conduction problem to a series of one-dimensional conductors, and a numerical solution can be utilized to achieve any desired/affordable degree of accuracy.

Nodes are identified in the model with alphanumeric names (allowing for simpler interpretation of results) and conductor connections are defined by specifying the names of the nodes to be connected. Conductors are further defined by material and transport properties, the mode of heat transfer

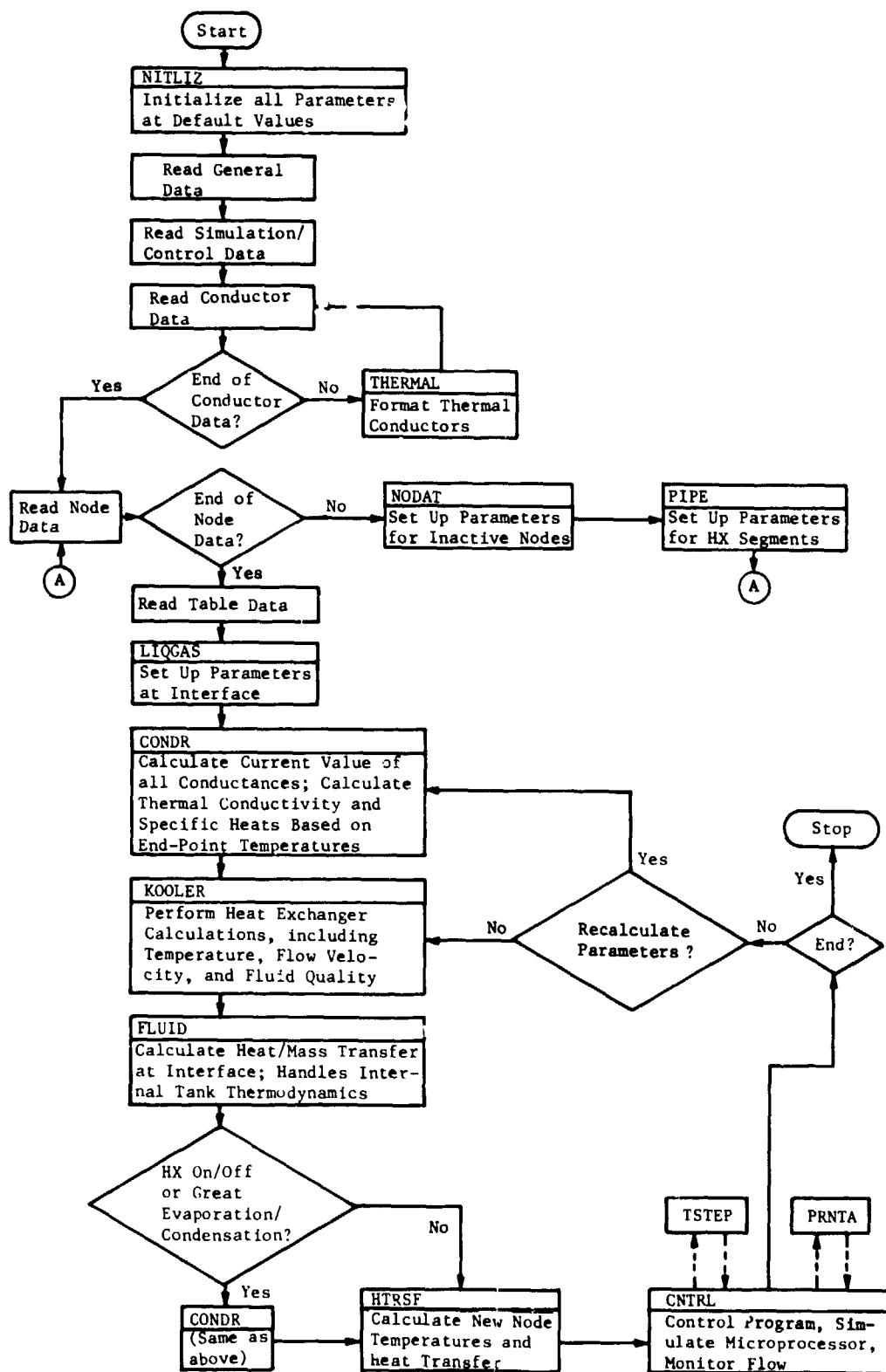


Figure V-4 CSAM Computer Logic Flow Diagram

(conduction, convection, and/or radiation), and the geometric information necessary for the system. A convective conductor between liquid and gas nodes is automatically converted into the proper parameters for calculation of heat and mass transfer at the liquid-gas interface. Heat exchangers of the thermodynamic vent system are also described by nodes/conductors, representing the heat exchanger tube segments and thermal connections to the bulk system. Nodes representing the fluid within the heat exchanger(s) and the conductors describing heat transfer from the fluid to the tube wall are automatically set up by the model. Any node may be specified to have a fixed temperature or a programmed temperature profile/cycle if this option is desired. Any conductor can optionally have a fixed heat flux (energy per time per area) or a fixed conductance (energy per time per temperature difference). These options allow boundary conditions to be defined in a realistic fashion, and also permit trade studies to be performed on various parameters.

The complexity of the model used to simulate the internal tank thermal and thermodynamic processes of the liquid and ullage within the storage tank is illustrated in Figure V-5. The CSAM computer program models all of the processes and factors shown on this figure for either a vapor-pressurized tank or the case when the ullage contains both vapor and a non-condensable pressurant.

The thermodynamic vent system is modelled by CSAM in a manner that accounts for the flow restrictor (valve/cojet) at the tank outlet, the two-phase and single-phase flow through the heat exchanger, and the heat transfer anticipated for the flow regimes at various qualities and differing magnitudes of gravity. The computer logic flow diagram for the TVS is shown in Figure V-6. Each heat exchanger can be broken up into as many nodes as desired to accurately model the system. (CSAM has the capability to model ten heat exchangers, each with separate flow characteristics and operating parameters) Each node is further described by many parameters such as its length, cross-sectional area, material type, connection with other nodes, and mass. The heat transfer from the heat exchanger tubes to the surrounding tank wall, vapor-cooled shield, penetrations, etc., is handled by the transient heat transfer network described previously since the modes of heat transfer are conduction and to a much lesser extent radiation. The subroutine in CSAM for the TVS handles the heat transfer between the fluid within the heat exchanger and the walls of the heat exchanger.

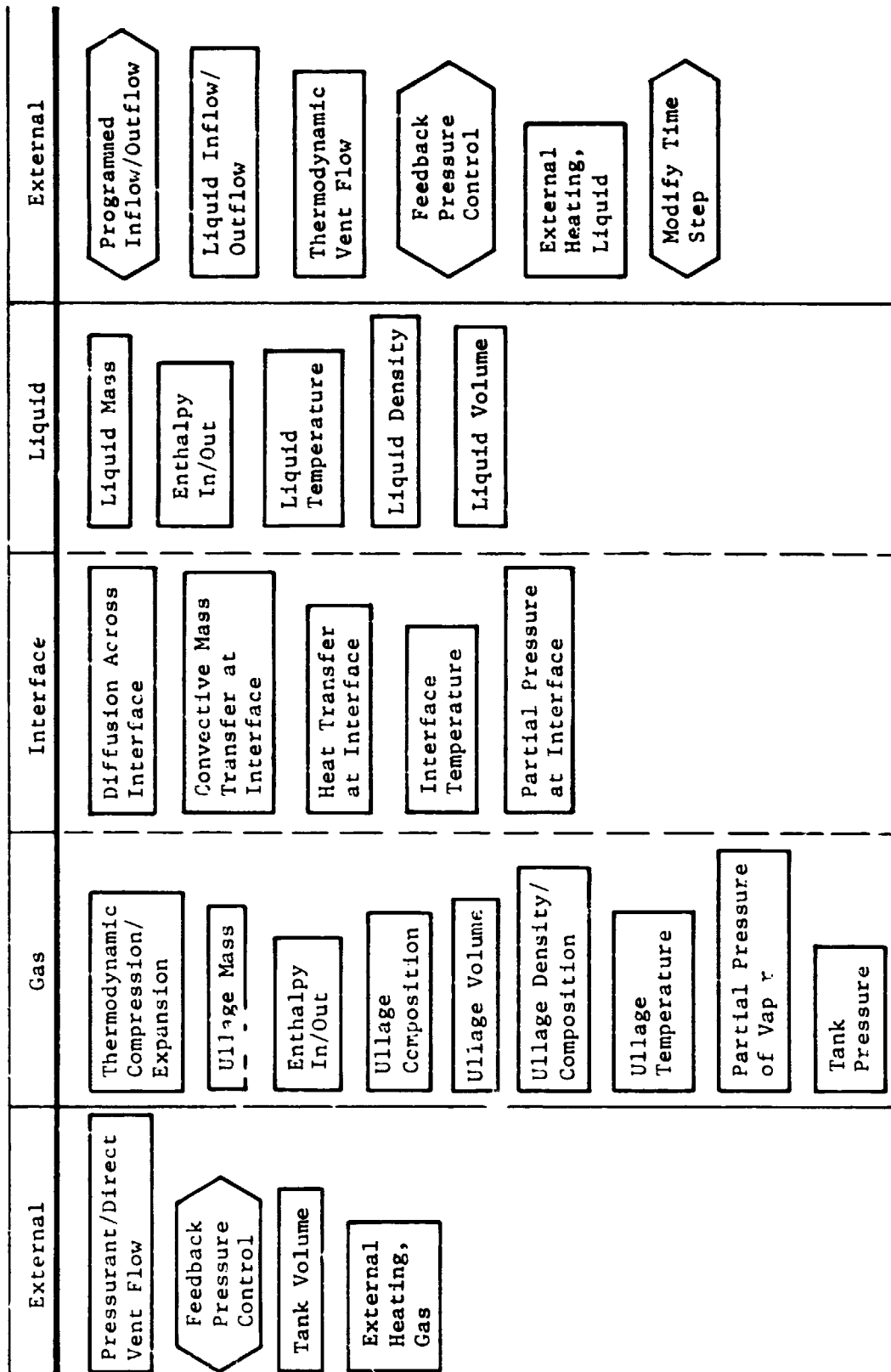


Figure V-5 Internal Tank Thermodynamics

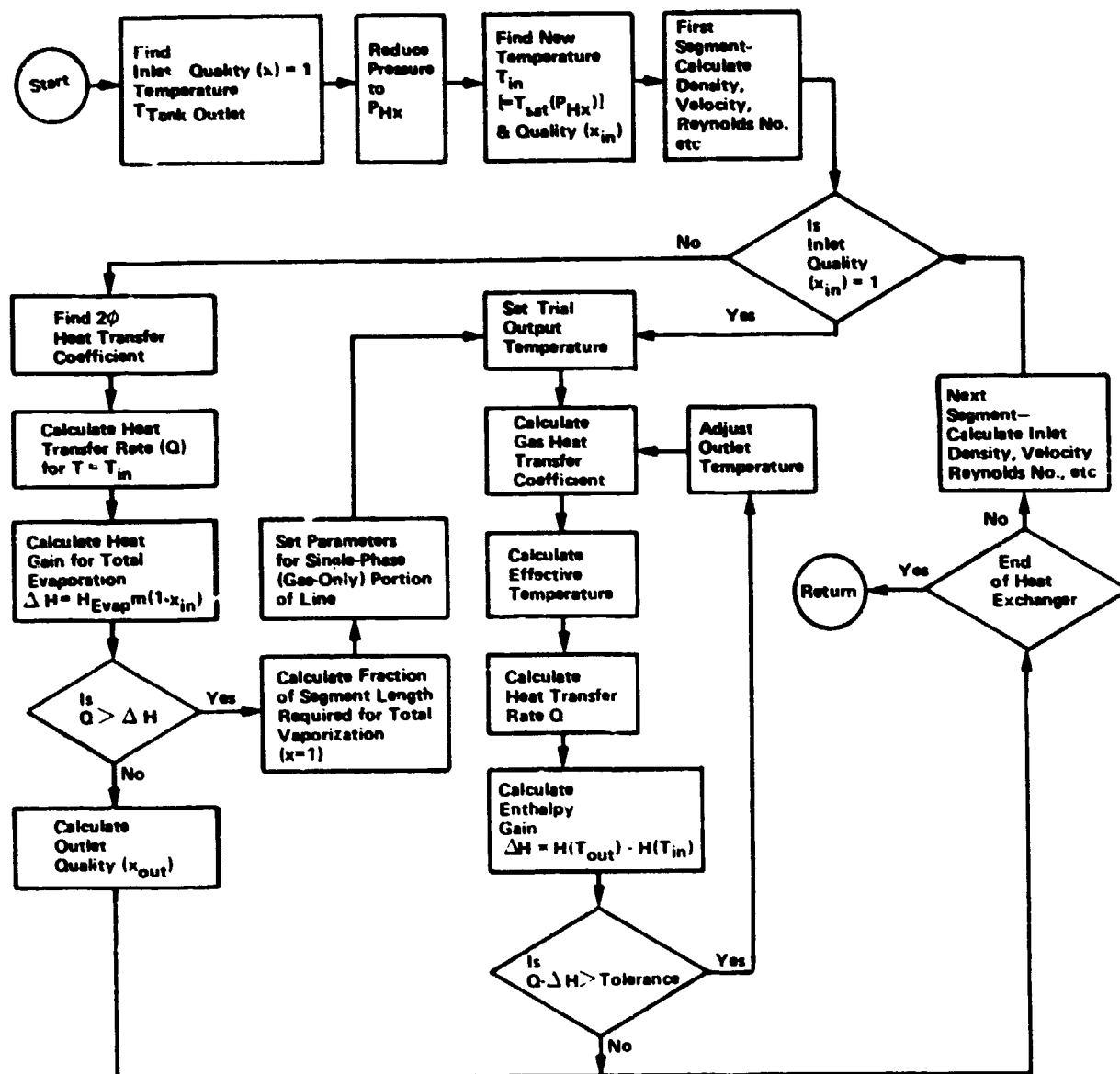


Figure V-6 Thermodynamic Vent System Model Logic

2. Storage Tank Assembly Thermal Analysis. Detailed analyses were performed of the components and subsystems within the vacuum jacket as well as the overall internal analysis of the storage tank. This included each component or subsystem that was thermally significant or complex, namely (a) the supports, vents, and other tank penetrations, (b) the multilayer insulation, (c) the helium pressurant spheres and the thermodynamics of the helium pressurant itself, and (d) the thermodynamic vent system including the flow restriction device, the heat exchanger lines, and the vapor-cooled shield. The results of these detailed analyses were modified for incorporation into the overall internal analysis. Because CSAM has the capability to accept fixed temperature or programmed temperature nodes and fixed conductance or fixed heat flux conductors, it was possible to input modified results from the detailed analyses into the overall analysis with little loss of accuracy but at considerable savings in computer usage.

The node-conductor network for the overall CFME analysis is illustrated in Figure V-7. The entire system within the vacuum jacket was assumed to be axisymmetric from "bottom" (liquid outlet) to "top" (pressurant inlet). The fluid was divided into two liquid nodes and one gas node, and the pressure vessel, VCS, and MLI were each divided into six nodes equally spaced in the axial direction. The MLI was further divided into two segments radially, each segment being half the total MLI thickness. Many trade studies were performed to determine the number of nodes necessary to adequately model the storage tank assembly. The addition of more nodes did not significantly improve the accuracy of the results and fewer nodes did not realistically simulate the thermal processes (e.g., one node for the storage tank would not allow stratification to develop and influence or be influenced by the internal fluid). For most cases, the optimum network consisted of 50 to 70 nodes and 70 to 110 conductors. However, some cases were analyzed in which a detailed component/subsystem model was incorporated without modification into the overall model to note its influence on the integrated system. After these results were evaluated, a representative component/subsystem model was selected for the overall model.

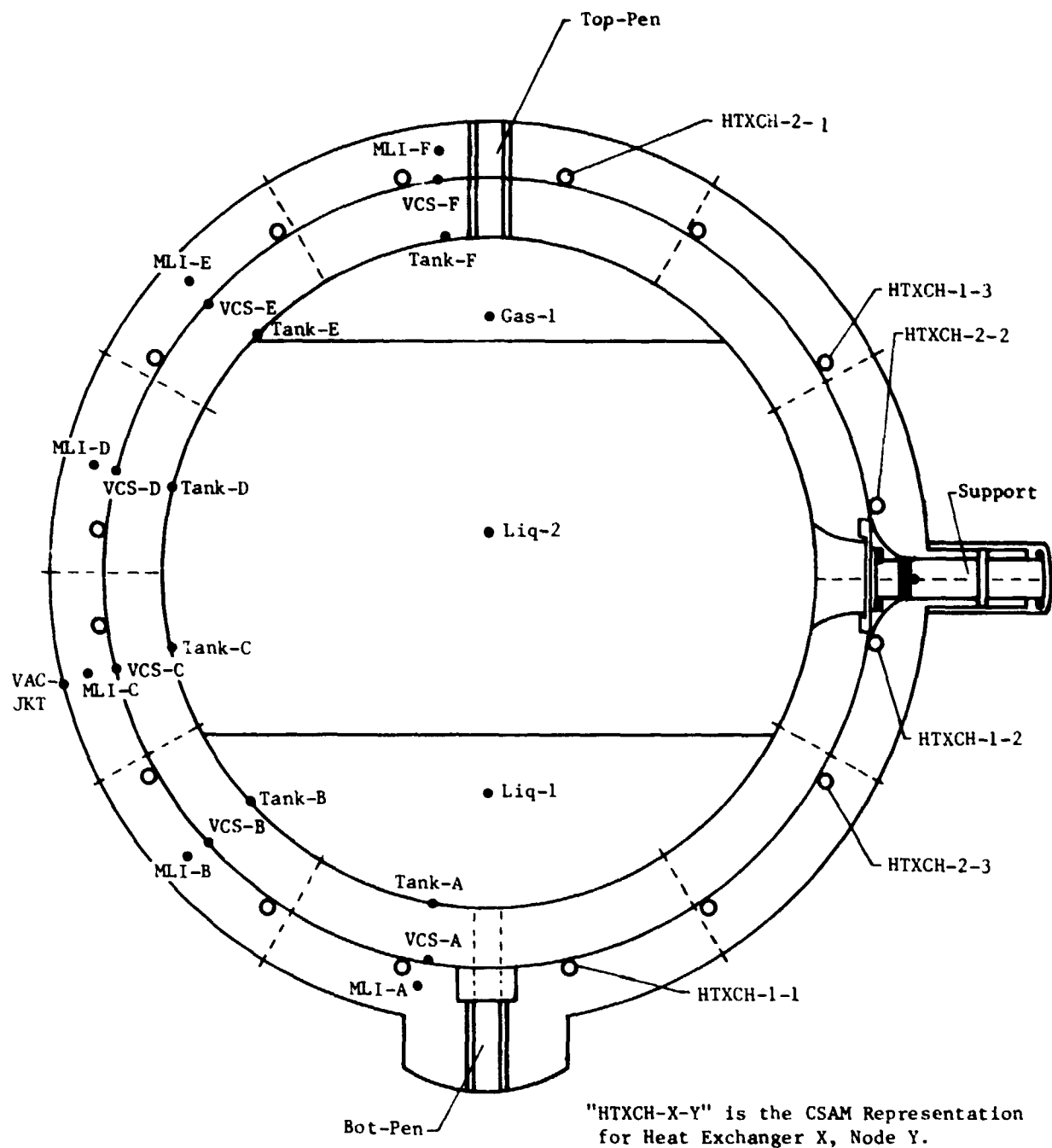


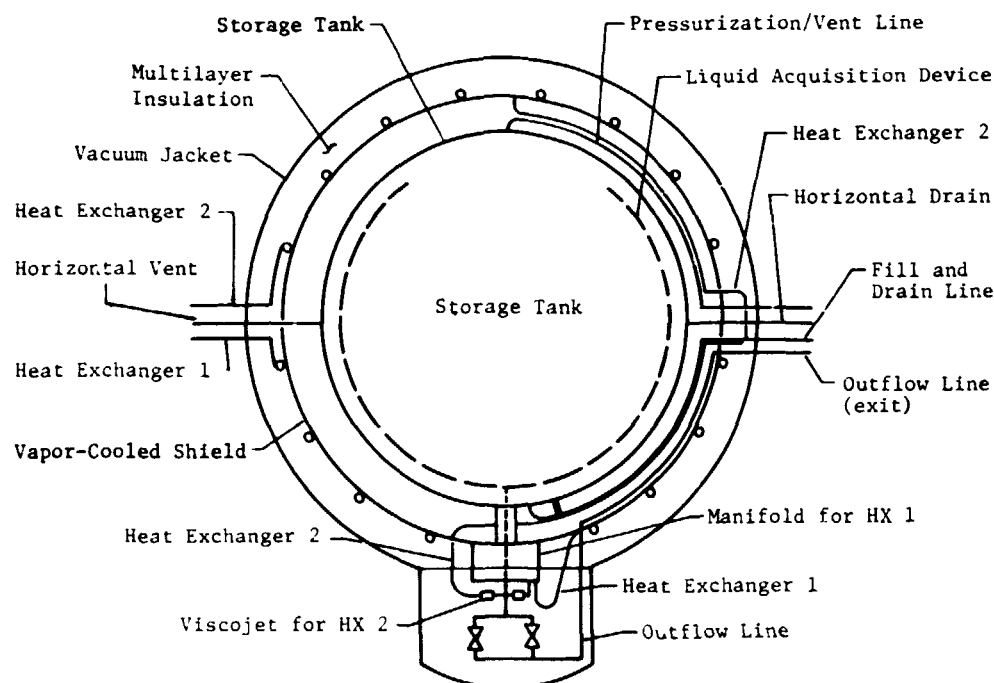
Figure V-7 CSAM Nodes for Storage Tank Assembly Thermal Analysis



A constant temperature of 294<sup>0</sup>K (530<sup>0</sup>R) was used for the single vacuum jacket node. This temperature is well above the mean temperature evaluated for any segment of the vacuum jacket in the external thermal environment analysis and conservatively models the CFME. This was important since a specific mission environment has not been defined for the experiment.

The heat inputs to the storage vessel occur as "distributed" heat inputs (through the MLI) and as "concentrated" inputs (through the penetrations). The distributed heat leak through the MLI has a low heat flux but has a large area for heat transfer by conduction and/or radiation. The concentrated heat inputs through various fluid lines, supports, and instrumentation wires have a high heat flux but relatively small areas for heat transfer, which is almost entirely by conduction. These concentrated heat inputs are referred to as "penetrations"; the design and analysis of these penetrations is of major thermal importance. This is evident from Table V-2 which gives a summary of the steady-state heat inputs to the liquid hydrogen storage vessel.

The various fluid line penetrations essential for operation of the CFME before, during, and after space flight are shown schematically in Figure V-8.



Detail is added to the bottom area of the CFME to illustrate the manifold as an integral part of heat exchanger 1.

Figure V-8 CFME Schematic Diagram

Table V-2 Steady State Heat Inputs to the Liquid Hydrogen Storage Tank

Penetration	Heat Input, Watts (BTU/hr)	
	TVS Inoperative	HX No.1 Operative
Multilayer Insulation	2.96 (10.10)	0.48 ( 1.65)
Supports	2.66 ( 9.09)	1.80 ( 6.13)
o Fixed	[1.16 ( 3.97)]	[0.76 ( 2.59)]
o Sliding	[1.16 ( 3.97)]	[0.76 ( 2.59)]
o Anti-Torsion	[0.34 ( 1.15)]	[0.28 ( 0.95)]
Fill and Drain Line	0.10 ( 0.34)	0.08 ( 0.27)
Outflow Line	0.12 ( 0.40)	0.12 ( 0.40)
Pressurization/Vent Line	0.19 ( 0.65)	0.01 ( 0.01)
Horizontal Vent Line	0.02 ( 0.08)	0.01 ( 0.01)
Horizontal Drain	0.02 ( 0.06)	0.01 ( 0.01)
Instrumentation Lead Wires to Pressure Vessel	1.34 ( 4.59)	0.07 ( 0.24)
Outflow Control Valve Lead Wires	0.04 ( 0.15)	0.01 ( 0.01)
Thermodynamic Vent Lines	1.45 ( 4.95)	0.57 ( 1.95)
o Heat Exchanger No. 1	[1.19 ( 4.07)]	[0.38 ( 1.29)]
o Heat Exchanger No. 2	[0.26 ( 0.88)]	[0.19 ( 0.66)]
TOTAL	8.91 (30.41)	3.12 (10.64)

It is important to note that all of the lines must provide good thermal performance while meeting the static, dynamic, and fluid loading requirements. For most lines, the thermal requirements are secondary to the other requirements and so the design is essentially fixed before any thermal analysis is performed. The location of the heat exchangers was the only exception to this design approach for the fluid lines. The lines were modelled by the transient heat transfer network in CSAM. Each line was broken into several nodes since the temperature drop along each line was dramatic and a larger number of nodes more accurately accounted for the temperature dependence of the specific heat and thermal conductivity. The resulting heat transfer through each line to the storage vessel was simplified and input to the overall internal analysis.

The support structure for the liquid hydrogen storage tank provides the other significant heat input. A fixed trunnion, a sliding trunnion, and an anti-torsion support located at the liquid outlet of the tank comprise these supports which are made of S-glass epoxy. Only limited information was available on the thermal properties of S-glass epoxy oriented along, at a 45-degree angle to, and perpendicular to the fiber axis. The model used to evaluate the heat inputs through the trunnions is shown in Figure V-9. This model assumes that all conduction in the radial direction is through S-glass epoxy oriented perpendicular to the direction of heat flow. Also, conduction along the length of the trunnion is divided such that 55 percent of the cross-sectional area represents axial fibers and 45 percent represents fibers oriented 45 degrees to the axis. Finally, the contact conductivity between the trunnion and the sleeve is  $1.14 \text{ kW/m}^2\text{-}^\circ\text{K}$  ( $200 \text{ BTU/hr-ft}^2\text{-}^\circ\text{R}$ ) with the area of contact being 5 percent of the rib area at its outer edge (the remaining 95 percent is connected to the sleeve via radiation with a view factor of 1.0 and an emissivity of 0.8). In using this model, many uncertainties became evident when determining areas for conduction and radiation view factors. A slight modification was made to omit the azimuthal breakdown (shown at the top of Figure V-9), allowing conduction and radiation paths to be more accurately defined. Although this reduced the detail of the central rib, the overall accuracy of the heat input to the storage tank was improved. The results of this analysis for the original single-mission trunnion and the current seven-mission trunnion are shown in Figure V-10.



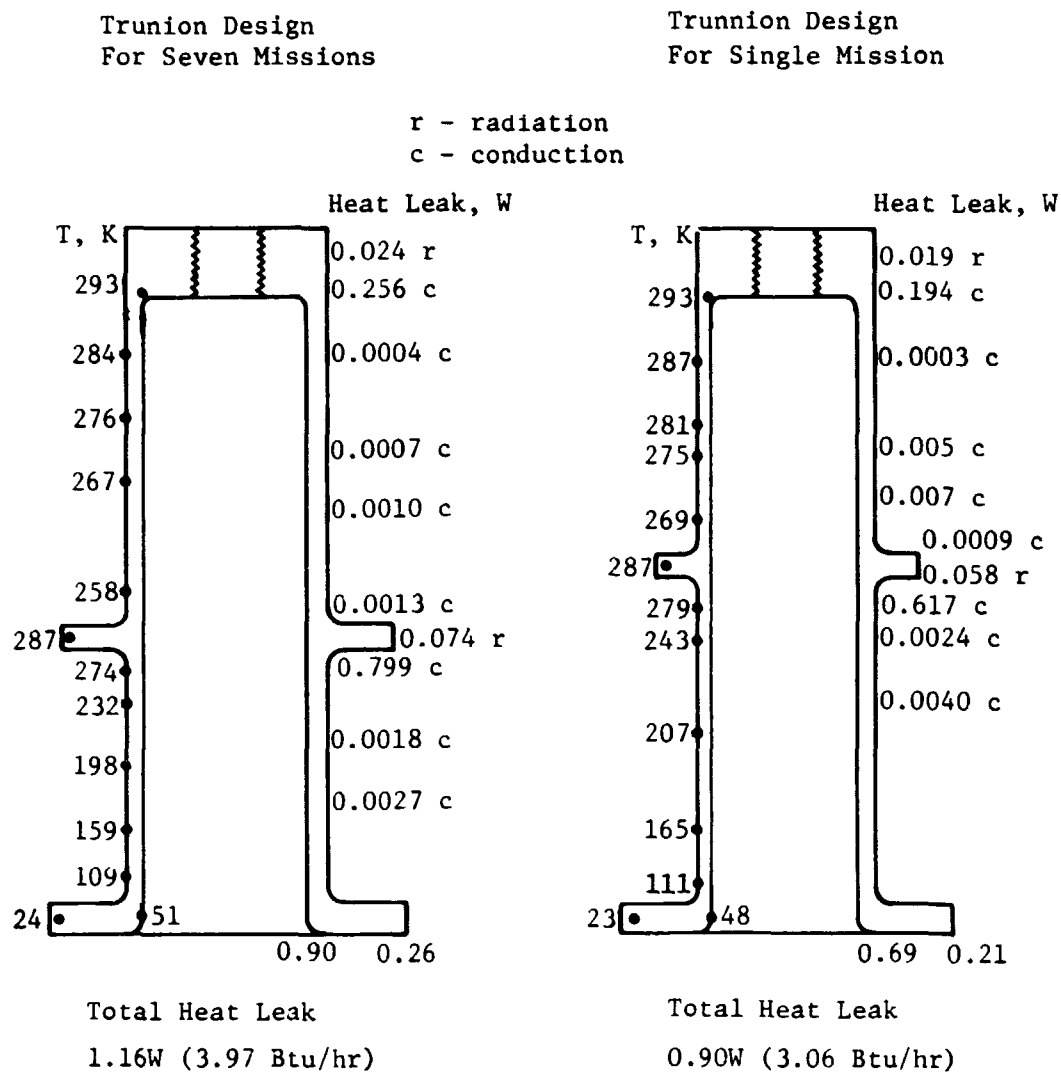


Figure V-10 Steady-State Trunnion Temperature Distributions and Heat Leaks

Another analysis comparing the fixed and sliding trunnion heat inputs showed the difference to be negligible. A similar analysis of the anti-torsion support produced the heat input noted in Table V-2. All of these support heat inputs were modified somewhat for incorporation into the overall internal analysis. The trunnions were first reduced to seven nodes and an analysis performed to investigate the effect of thermally shorting some of the trunnion heat input to the VCS. After this study was completed, the resulting heat input to the storage tank during each mode of operation was input to the overall internal analysis.

The multilayer insulation (MLI) consists of layers of 6.35  $\mu\text{m}$  (0.25-mil) double-aluminized Mylar with two B4A Dacron nets between each reflector. The selection of this insulation system was based on research conducted by the Lockheed Missile and Space Company on contract to the NASA Lewis Research Center (Ref. 22 and 23). The MLI has a layer density of 2.4 layers per millimeter (60 layers per inch) with each layer consisting of one reflector and two Dacron nets. The density is approximately  $56.2 \text{ kg/m}^3$  ( $3.51 \text{ lbm/ft}^3$ ) without fastening materials and protective cover.

For modelling, the MLI was divided into six nodes axisymmetrically and two conductors radially. As the VCS temperature varies due to transient effects and intermittent heat exchanger operation, the effective thermal conductivity changes. It was assumed that there was negligible heat transfer from one MLI node to another. This was demonstrated to be a fairly good assumption by evaluating the radiation view factors between adjacent layers of insulation (very close to unity, even for small segments of MLI).

The helium pressurization system is used for normal orbital operation, orbital abort, and ground abort mission events. This system consists of the MLI-insulated pressurant spheres, the lines interfacing with the spheres, and the helium itself. Cost and size trade studies indicated that the preferred approach for pressurant storage spheres was to use off-the-shelf 6Al-4V titanium spheres with a nominal inside diameter of 348-mm (13.7-in) and an operating pressure of  $21.6 \text{ MN/m}^2$  (3135 psia) at 303<sup>0</sup>K (545<sup>0</sup>R). Each sphere holds 0.69 kg (1.51  $\text{lb}_m$ ) of helium at the maximum operating pressure. The lines from the spheres to the pressure vessel are 64-mm (0.25-in) O.D. tubing.

The helium temperature, pressure, and mass at the inlet and within the storage tank were modelled using CSAM during normal mission operation. The temperature of the helium within the pressurant spheres was determined from a detailed external thermal analysis of the CFME. This helium temperature profile was modified to account for heating in the lines and heating due to Joule-Thomson expansion. The modified temperature profile was then input into CSAM for the mission simulation.

The thermodynamic vent system (TVS) is a sophisticated heat exchanger network made up of many components with unique functions. Liquid is supplied from the storage tank through the liquid acquisition device. Upon demand, liquid is drawn from the LAD, through a flow restriction device and into a heat exchanger line. The flow restrictor, aided by the vacuum of space, reduces the internal heat exchanger fluid pressure substantially below tank pressure. Part of the vent liquid vaporizes during this process and the two-phase mixture is at a lower temperature than the tank liquid, corresponding to its saturation temperature at the new pressure. The fluid is routed through a manifold around the outflow line where it absorbs heat from the outflow line and indirectly from the tank fluid. The fluid is then routed along the vapor-cooled shield to intercept a fraction of the "distributed" heat leak to the storage tank, and along the various penetrations to intercept some of the "concentrated" heat leak. When the heat exchanger fluid temperature reaches the tank fluid temperature it is completely vapor and is slightly superheated. The vapor is finally vented to space when its cooling capability has been exhausted.

The tank pressure is controlled by the TVS and can be reduced in several ways during efficient TVS operation. The small rate of liquid outflow necessary to operate the TVS expands the ullage slightly and reduces the pressure accordingly. The TVS can also cause condensation or decrease the gas temperature.

Overall performance of the CFME during the baseline seven-day orbital mission defined in Chapter III is shown in Figures V-11 and V-12. A profile of the tank pressure as a function of time and the mass of helium admitted with time are presented in Figure V-11. The depletion of fluid in the tank through the mission due to saturated and subcooled liquid outflow and thermodynamic venting is shown in Figure V-12.

The baseline CFME mission sequence is as follows. The flight timeline of the experiment is activated at liftoff (time zero) with 39 kg (85 lbm) of liquid hydrogen in the storage vessel at  $103 \text{ kN/m}^2$  (15 psia) and heat exchanger 1 of the TVS enabled. This heat exchanger remains on throughout the mission. In a brief amount of time, the g-vector is reduced dramatically as the CFME reaches its orbit. (In the CSAM simulation, the g-vector is 1.0

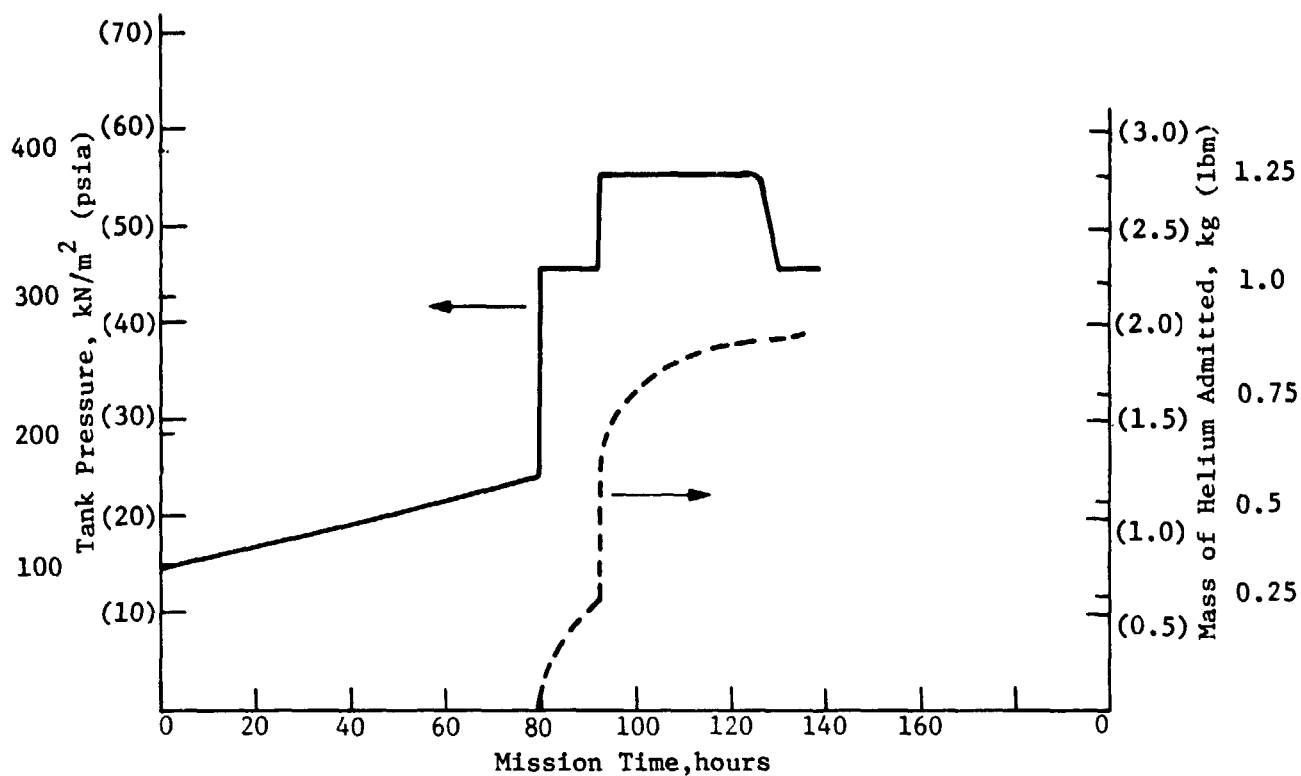


Figure V-11 CFME Pressure History and Helium Requirements for Seven-Day Baseline Mission

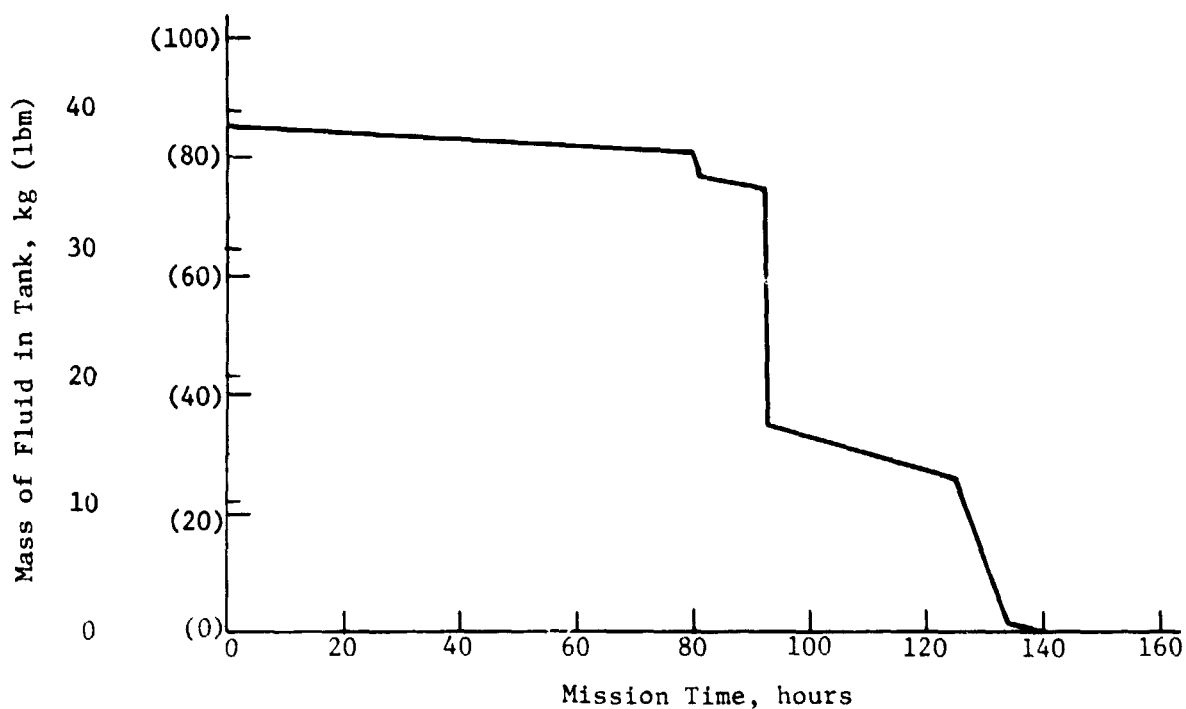


Figure V-12 Mass of Hydrogen Remaining in Storage Tank Throughout Seven Day Baseline Mission



during ground hold and is changed to 0.0001 at time zero; no attempt is made to simulate the launch acceleration and vibration during this brief period). An 80-hour inactive period is provided so that thermal conditions within the pressure vessel can stabilize and data can be gathered on the TVS performance. Since heat exchanger 1 is sized to reduce the steady state heat input by 60-80 percent, the tank pressure continues to rise. Heat exchanger 2 of the TVS is set to activate at pressures of  $317 \text{ kN/m}^2$  (46 psia) or higher. At 80 hours into the mission, the helium pressurization set point is raised to  $310 \text{ kN/m}^2$  (45 psia). At this time, the first outflow is performed. Liquid hydrogen (slightly subcooled) is delivered at a flow rate of 1.5 kg/hr (3.3 lbm/hr) for a period of 1.2 hours, as seen in Figure V-12. During the outflow, helium is admitted as necessary to maintain tank pressure at  $310 \text{ kN/m}^2$  (45 psia).

Following the outflow, the tank pressure is kept at  $310 \text{ kN/m}^2$  (45 psia) for 11 hours. During this time it is necessary to alternately pressurize with helium and operate heat exchanger 2. This is necessary because the warm helium,  $194\text{--}256^\circ\text{K}$  ( $350\text{--}460^\circ\text{R}$ ), enters the ullage and increases the tank pressure and gas temperature. As the warm gas transfers heat to the cool interface, two significant phenomena occur. First the hydrogen evaporates more rapidly since there is a greater rate of heat transfer to the interface. Second, the gas temperature drops as the heat is used to provide for the vaporization of hydrogen and some heating of the liquid. The former process leads to an increase in pressure while the latter results in a pressure decrease. The net change is a slight pressure increase since both mass and energy are added to the ullage.

The helium pressurization overshoot and the above effect yield a pressure rise to over  $317 \text{ kN/m}^2$  (46 psia), not just the  $310 \text{ kN/m}^2$  (45 psia) set point. This activates heat exchanger 2, which eventually drops the pressure below  $317 \text{ kN/m}^2$  (46 psia). However, the pressure continues to drop slightly after heat exchanger 2 is disabled due to the cold stagnant fluid within the heat exchanger and the continued cooling of the ullage. The pressure falls below  $310 \text{ kN/m}^2$  (45 psia) and the helium pressurant again enters the pressure vessel. These problems in operation of alternately pressurizing and then cooling to remove the heat introduced due to pressurization could be

reduced by increasing the pressurization band width from  $\pm 7 \text{ kN/m}^2$  (1 psi) to  $\pm 7 \text{ kN/m}^2$  (2 psi) and/or by only activating the pressurization system for the pressure-regulated outflow periods. The latter approach is recommended.

Following the 11-hour storage period, the setpoint of heat exchanger 2 is raised to  $386 \text{ kN/m}^2$  (56 psia) and helium pressurization is activated to raise the pressure to  $379 \text{ kN/m}^2$  (55 psia). Expulsion of subcooled liquid hydrogen at a flowrate of 27 kg/hr (60 lbm/hr) begins soon after  $379 \text{ kN/m}^2$  (55 psia) is reached. This outflow continues for 40 minutes and helium is injected to maintain tank pressure at  $379 \text{ kN/m}^2$  (55 psia).

A 33-hour storage period follows the second expulsion, and it is evident that some additional helium is required for the first several hours of this period. This is necessary because the large ullage is composed of warm helium and hydrogen vapor. As heat transfers from the gas to the tank wall and the liquid, the gas cools considerably, requiring more helium for about 10 hours. For the remaining 23 hours of the storage period, heat exchanger 2 is activated and operates almost continuously to cool the ullage and condense hydrogen vapor. This again demonstrates the desirability of locking out the pressurization system except for periods of regulated outflow.

The setpoint for operation of heat exchanger 2 is reduced to  $317 \text{ kN/m}^2$  (46 psia) at a mission time of 126 hours. The helium pressurization set point is dropped to  $310 \text{ kN/m}^2$  (45 psia) at the same time and liquid hydrogen expulsion begins at a flowrate of 1.5 kg/hr (3.3 lbm/hr). This subcooled outflow permits blowdown of the tank pressure and continues for 8 hours. If the tank pressure drops to  $310 \text{ kN/m}^2$  (45 psia) during this outflow, helium pressurant will be admitted to maintain this pressure. Since blowdown of tank pressure imposes the worst-case thermal conditions on the LAD, this expulsion should establish if any two-phase flow will occur.

After 8 hours of outflow, the helium pressurization system is reset to  $379 \text{ kN/m}^2$  (55 psia) and the heat exchanger 2 set point is returned to  $386 \text{ kN/m}^2$  (56 psia). Following an 8-hour storage period at these conditions, a final expulsion should begin at the same flowrate of 1.5 kg/hr (3.3 lbm/hr) and should result in outflow of subcooled liquid hydrogen. However, the storage tank is depleted prior to this scheduled outflow due to the excess operation of heat exchanger 2, as discussed above.

One method of resolving this problem is to lockout the helium pressurization system during periods of storage (no liquid outflow). A CSAM simulation of the mission with this constraint is presented in Figures V-13 and V-14. In this scenario, helium pressurant is only added to maintain pressure at the prescribed level during outflow. Immediately following each of the first two expulsions, the pressure in the tank drops, reflecting the saturation pressure rise corresponding to the new thermodynamic conditions of the fluid. Prior to the third expulsion (blowdown), the fluid is already saturated at about  $310 \text{ kN/m}^2$  (45 psia), so the tank pressure following the expulsion is at a higher value corresponding to the higher saturation pressure.

This method of operation results in a more efficient utilization of the stored hydrogen. About 20 percent less helium is required prior to normal storage tank inerting using this helium pressurization system lockout technique. Also, an additional 2.7 kg (6.0 lbm) of liquid is available for experimental outflow since it is not vented through heat exchanger 2 of the TVS.

3. CFME Payload Thermal Analysis. An analysis was performed to evaluate the thermal environment to which the external surfaces of the CFME could be exposed during the mission. Figure V-15 illustrates the steps followed in the analysis to obtain the temperature profiles of various elements of the system as a function of mission time.

The worst-case hot and cold temperature extremes for the pallet, and Orbiter location and orientation with respect to the Earth and Sun, were input to the Thermal Radiation Analysis System (TRASYS) computer program, and absorbed solar fluxes and associated view factors for the various CFME elements were obtained. These radiation parameters together with the pallet temperature profile, shown in Figure V-16 (see Chapter II also), were then used in a CSAM model of the CFME in the cargo bay to calculate the temperature profiles of the CFME elements. These profiles are shown in Figure V-17 for the case of no heat dissipation from the DACS power distribution units. For this case, the maximum temperatures reached by several of the elements exceeded practical allowable limits.

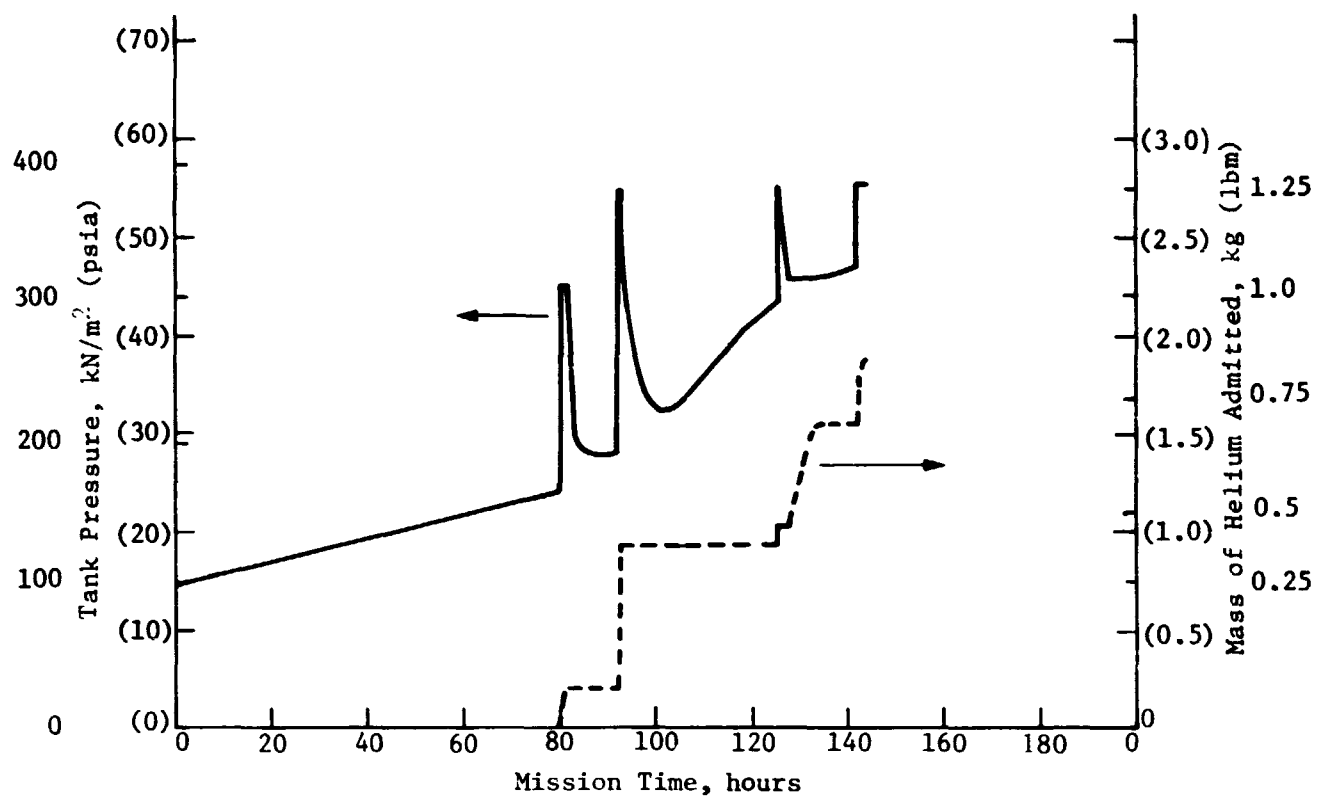


Figure V-13 Revised CFME Pressure History and Helium Requirements

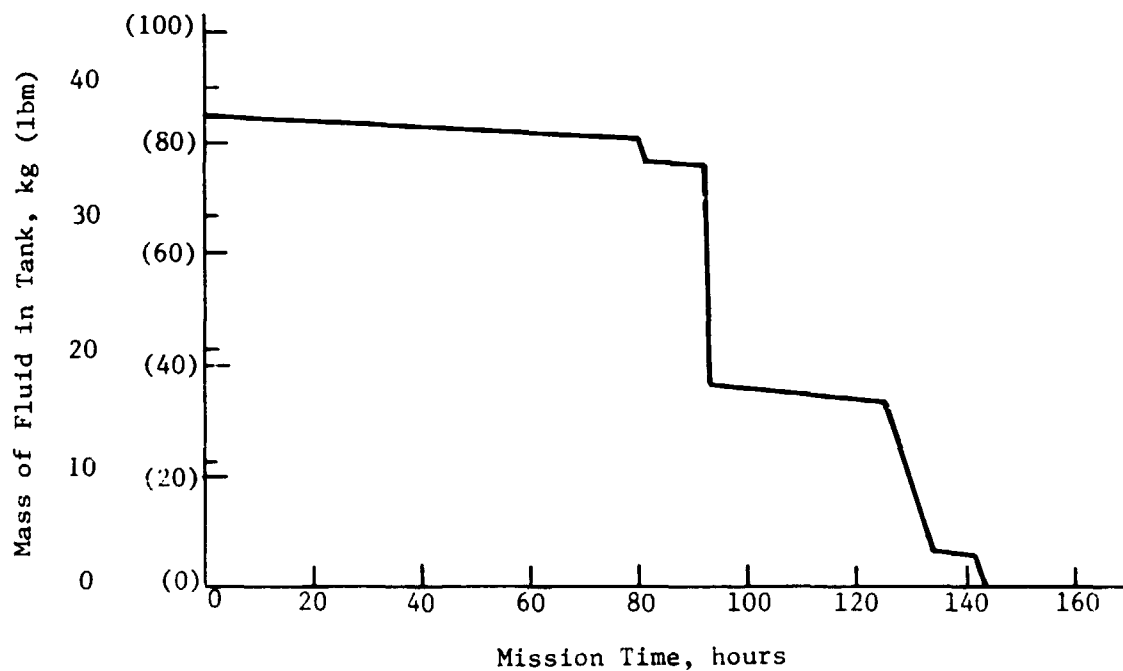


Figure V-14 Revised Hydrogen Storage Mass Throughout Seven Day Mission

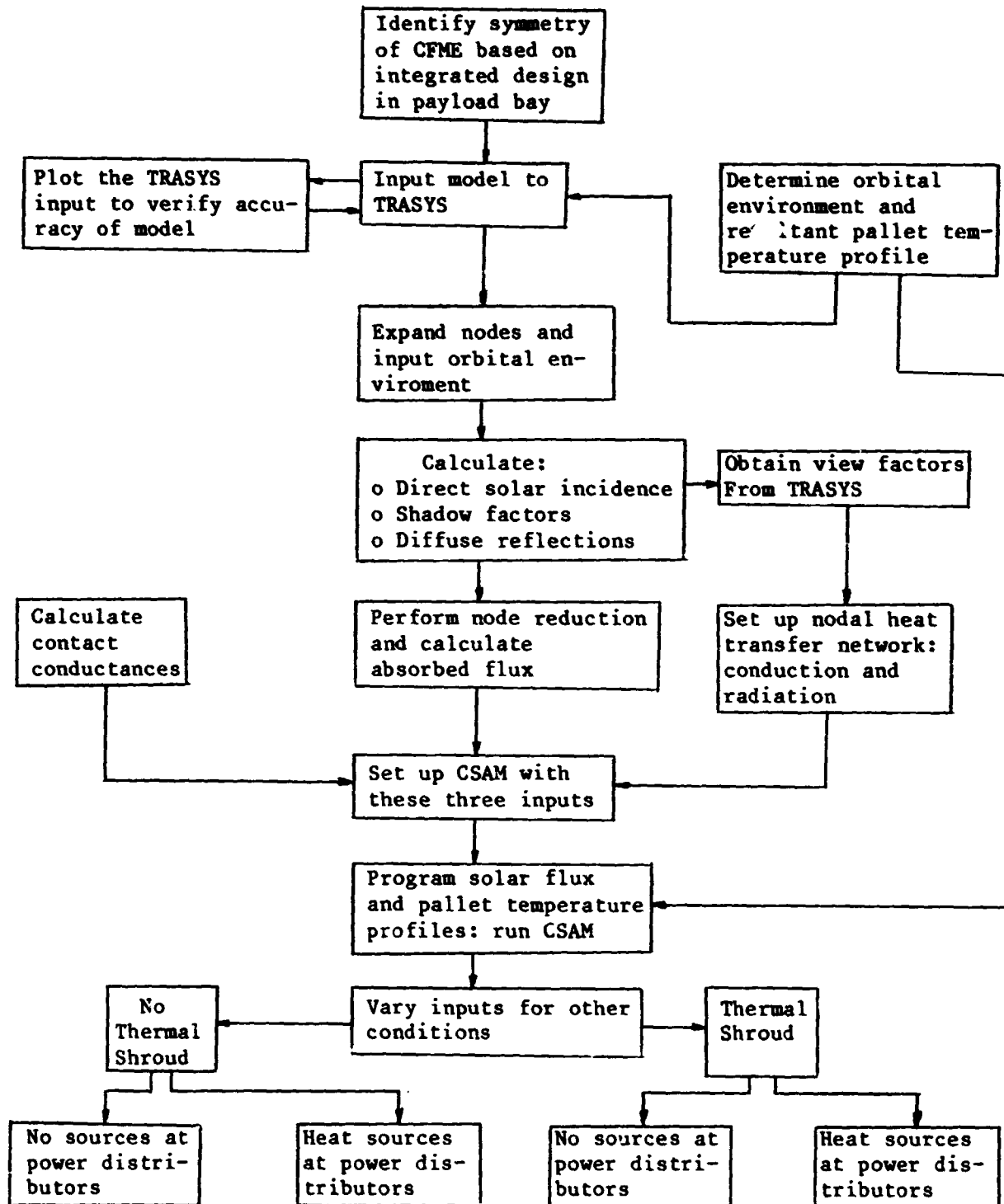


Figure V-15 CFME External Environment Analysis Flowchart

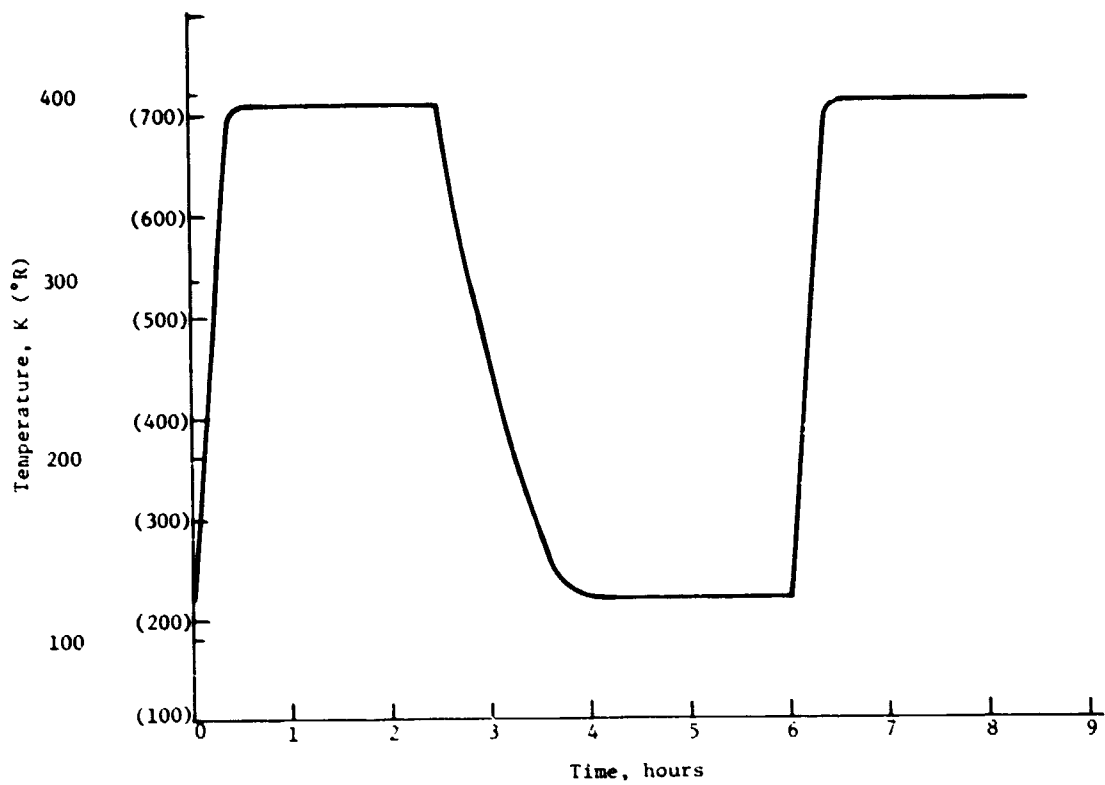


Figure V-16 Spacelab Pallet Temperature Versus Time

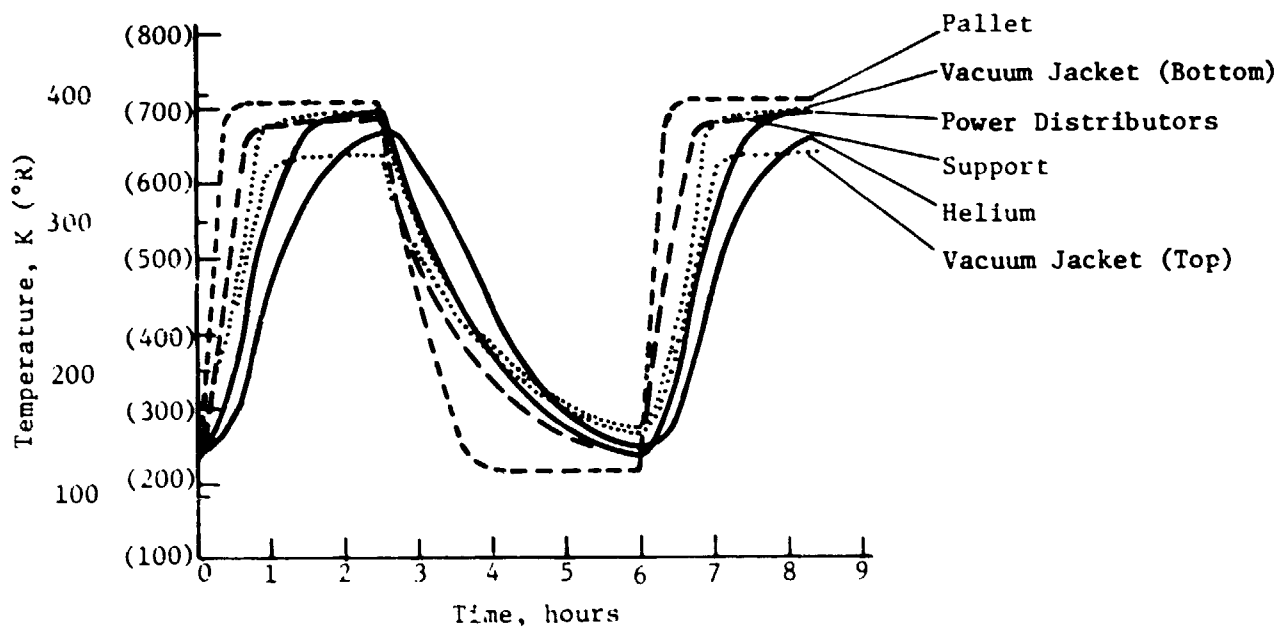


Figure V-17 CFME External Temperature Profiles (No Shroud/No Power)

An evaluation was then performed with the experiment encased in a thermal shroud. The shroud included in the analysis was assumed to reduce the solar flux by 2/3. Since the pallet was no longer exposed to direct radiation from the sun or to space, the pallet temperature profile in Figure V-16 was no longer valid. Because of this, the maximum hot and cold pallet temperatures predicted for Spacelab Mission 2 (Ref. 24) were assumed to apply and the profile of the 6-hour cycle was modified, as shown in Figure V-18.

The results of this analysis are shown in Figures V-19 and V-20 for the cases with no heat source at the power distributors and 38 W (130 Btu/hr) at each distributor, respectively. The latter case corresponds to the maximum heat generation from the CFME electronic boxes. The thermal shroud reduces the maximum temperatures and raises the minimum temperatures to levels acceptable for all CFME components.

It is recommended that a detailed thermal analysis be performed again for the CFME external environment when a specific mission and payload parameters are more accurately defined.

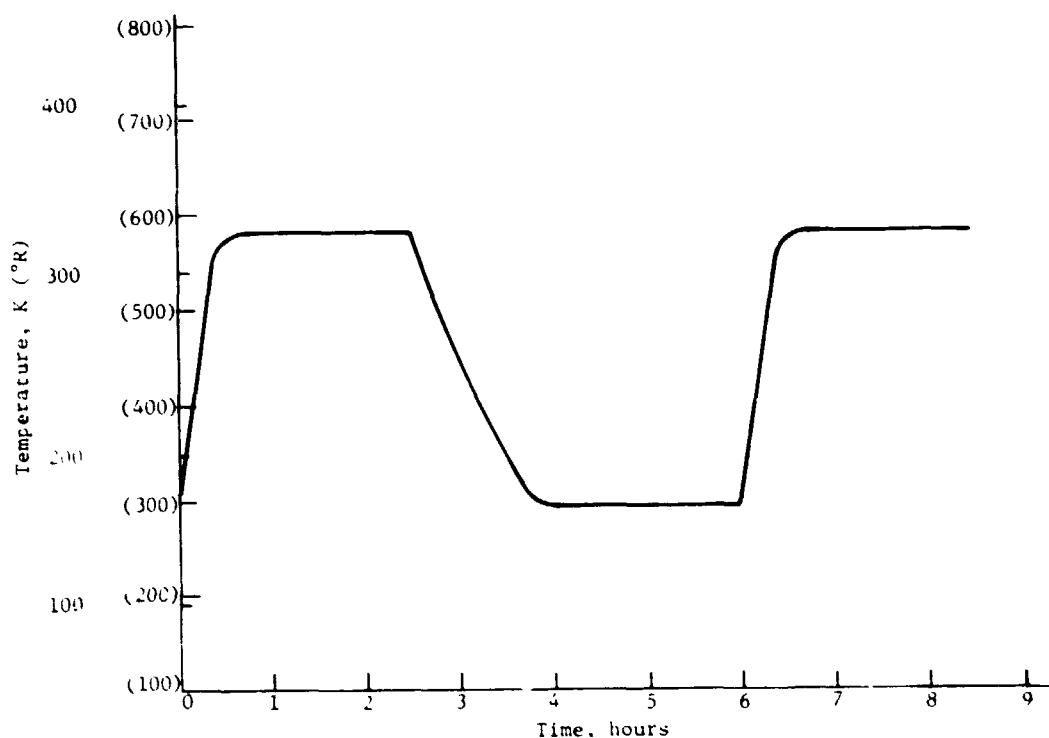


Figure V-18 Spacelab Pallet Temperature Profile with Thermal Shroud

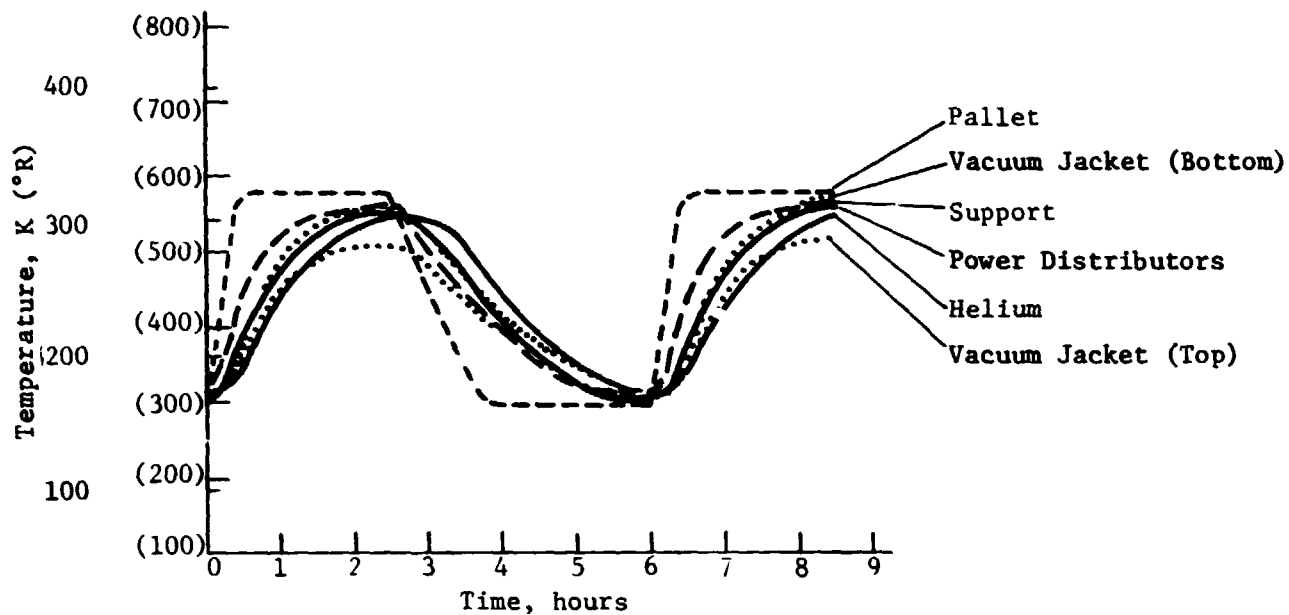


Figure V-19 CFME External Temperature Profiles (Shroud/No Power)

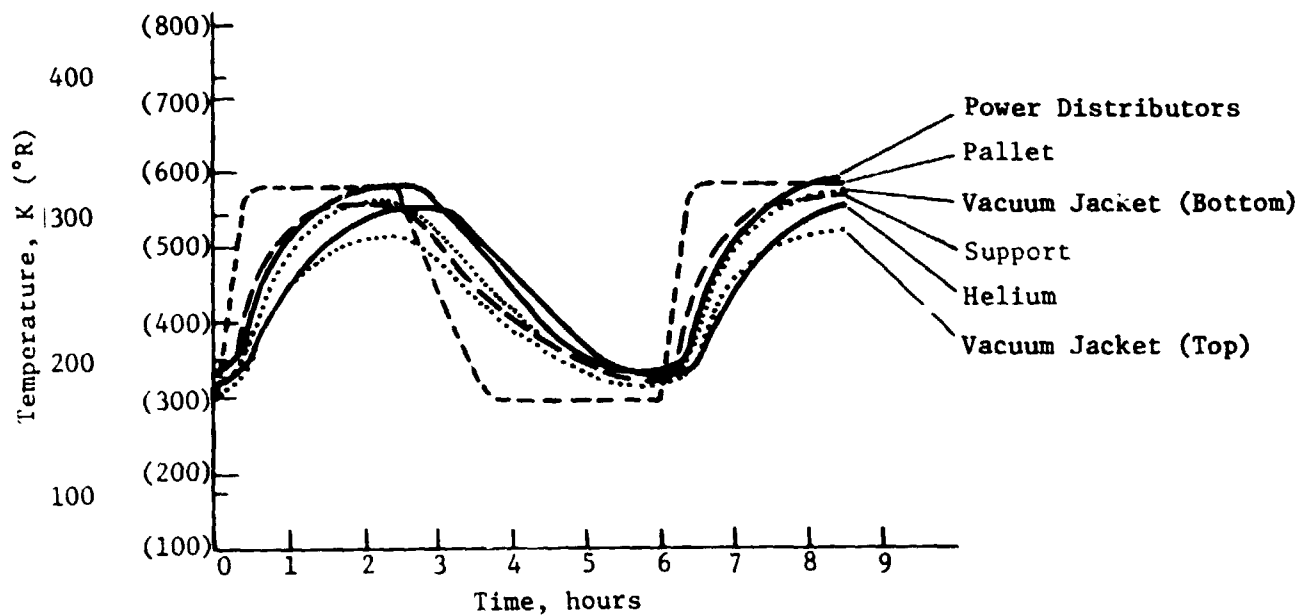


Figure V-20 CFME External Temperature Profiles (Shroud/Power)



### C. Structural Analysis.

This section presents a summary of the structural analysis conducted on the CFME. Additional details of the analysis are contained in the Structural Analysis Report (Ref. 21).

1. Structural Design Approach. The structural analysis approach, and evolution, since contract award is delineated in Figures V-21 and V-22. A preliminary structural analysis was conducted and presented at PDR (June 1979). This analysis concentrated primarily on the tank and support structure (e.g., storage tank, girth ring, trunnions, LAD, bipods). Figure V-21 details the analysis approach up to PDR.

In May 1980, Modification 6 to the contract was issued. This modification introduced a seven mission requirement on the experiment, and modified the testing approach to include a test article (CFME-TA). At the same time, Appendix B01 to the SPAH SLP/2104 was incorporated into the contract. This Appendix imposed a pallet-hardpoint deflection criteria on the experiment.

The analysis approach subsequent to incorporation of Modification 6 is shown in Figure V-20. The analyses include consideration of the new Modification 6 requirements, and reflect the final CDR design. The following paragraphs present a summary of these analyses and identify any potential problem areas for future consideration.

2. Dynamics and Loads Analysis. During flight operations, the experiment is exposed to vibrational loads which may be categorized into two frequency regimes:

- o Quasi-static (low frequency,  $< 35\text{Hz}$ ) caused by STS and experiment response to transient events such as engine ignition, staging, overpressure, and landing.
- o Random (high frequency, 20-2000 Hz) caused by mechanically transmitted random vibration at the experiment/pallet interface due to STS response to the liftoff acoustic field. Additional loading results from experiment response to the incident acoustic environment in the Shuttle cargo bay.

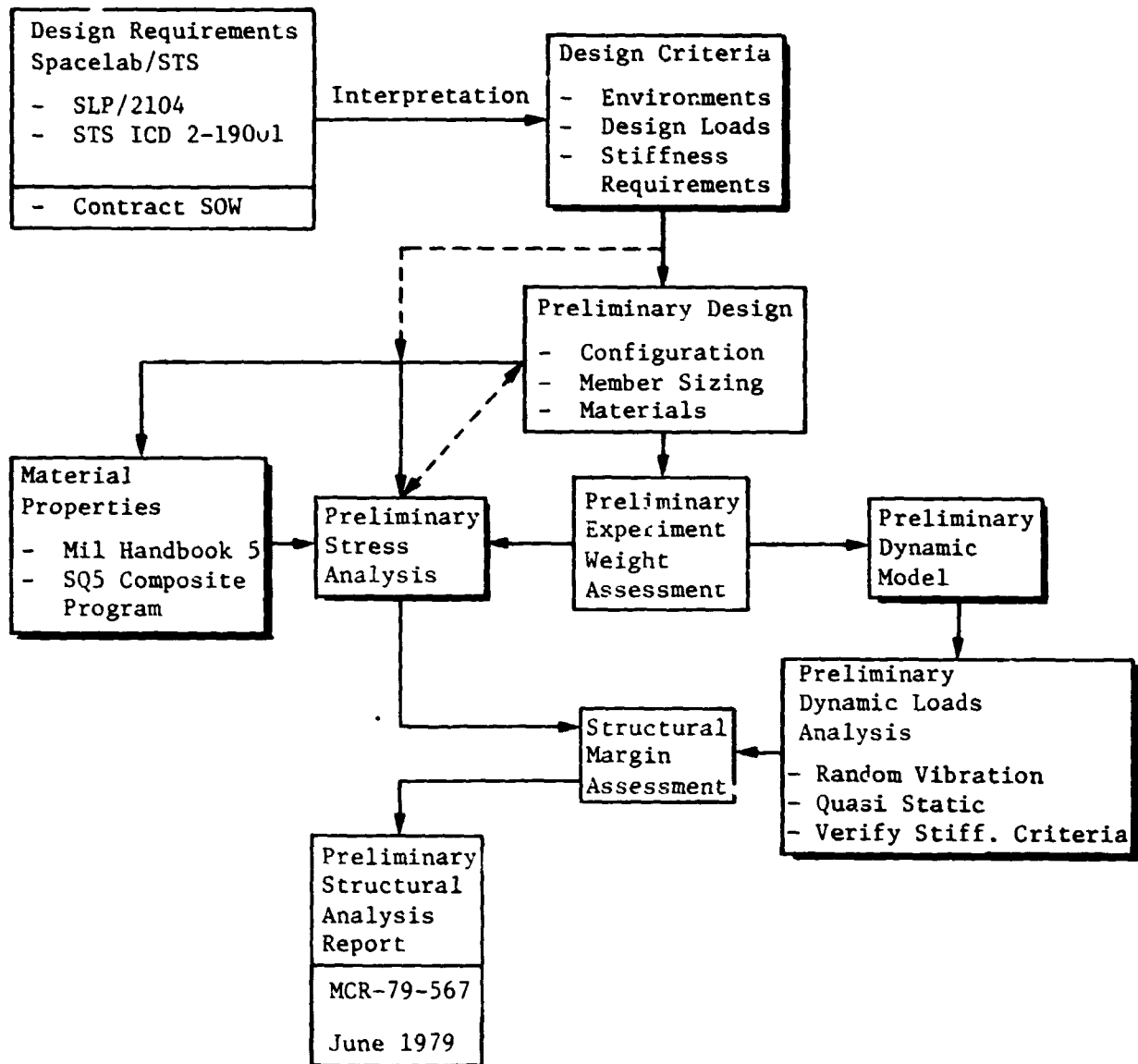


Figure V-21 Structural Analysis Approach (to PDR)

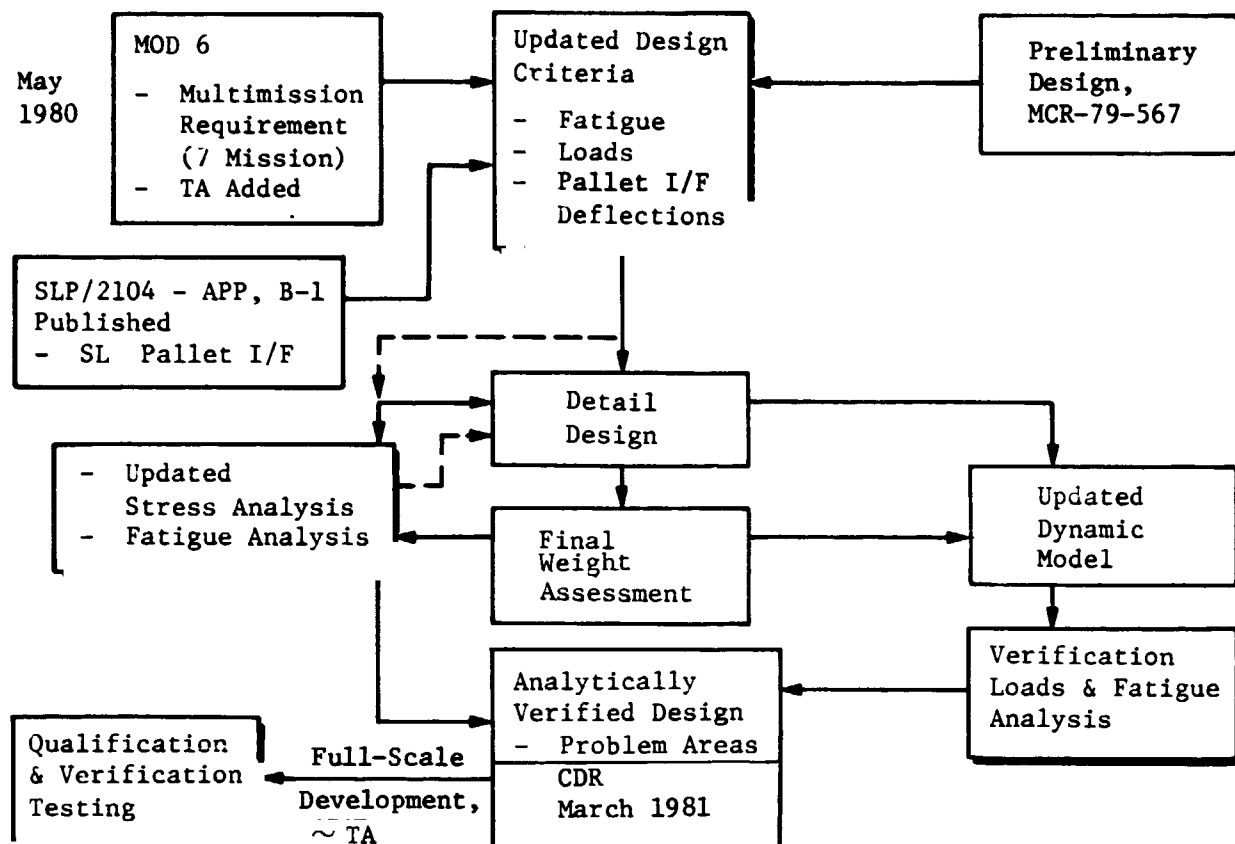


Figure V-22 Structural Analysis Approach (PDR to CDR)

The loads resulting from these environments must be combined to result in the total experiment load. SPAH SLP/2104 requires a direct combination (sum).

Table V-3 lists the quasi-static design limit load factors derived from SPAH SLP/2104. These load factors are for pallet-mounted payloads whose fundamental natural frequency (cantilevered at the pallet interface) is greater than 35 Hz. The major STS response to transient events occurs in the frequency range from 4-35 Hz. Payloads having fundamental frequencies above this range will respond, more or less, as rigid bodies. Lower frequency payloads could couple with STS transient events, resulting in higher loads than those in Table V-3. As discussed in SPAH SLP/2104, final verification of dynamic loads should be accomplished by a coupled dynamic loads analysis on the entire mission payload.

The Spacelab pallet random vibration environment is 8.72 grms, as presented in Chapter II. An equivalent random vibration load factor of 8.2g was derived using Miles' equation to facilitate structural sizing. This load factor was derived assuming a 50 Hz fundamental frequency and 2 percent of critical damping. A basedrive random vibration analysis was conducted to confirm the predicted random vibration loads.

Verification of the CDR design has been accomplished through a finite element dynamic analysis. Figure V-23 delineates the overall analysis approach. A summary of the analyses (highlighted blocks) is presented in the following sections.

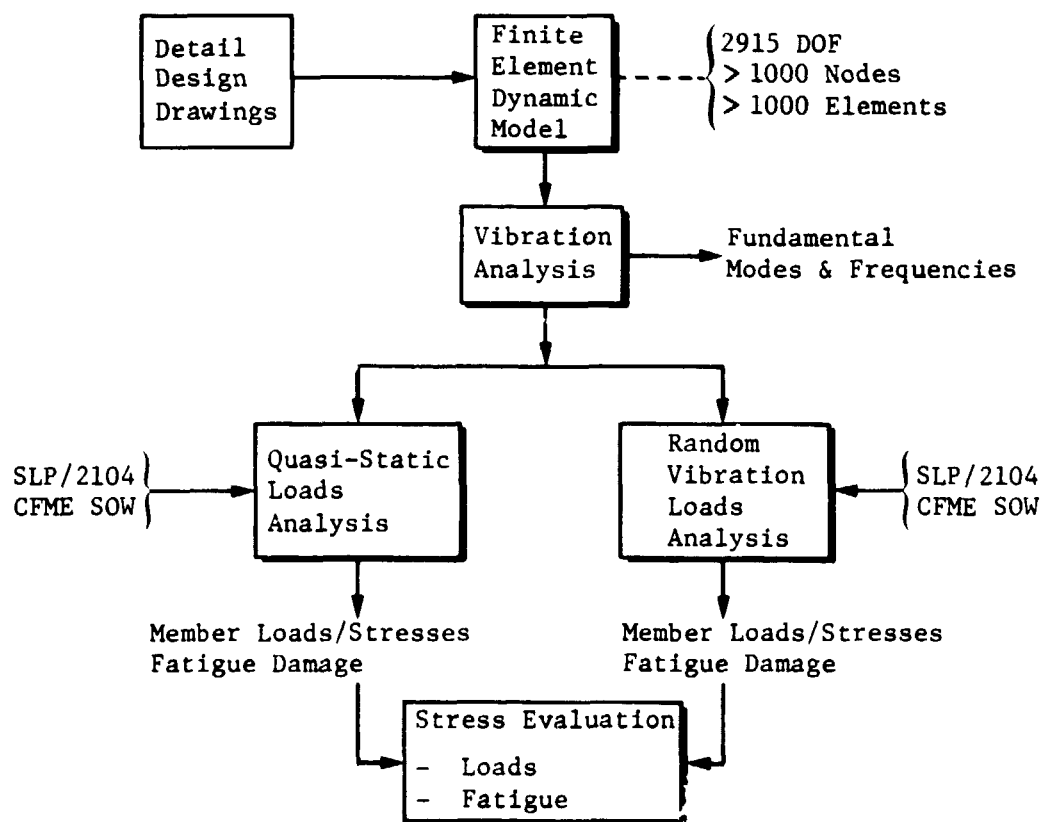


Figure V-23 Verification Structural Analysis

Table V-3 CFME Quasi-Static Load Design Factors

Load Direction	Limit Load Factor (g)
X	+ 4.3 - 4.3
Y	+ 1.4 - 1.4
Z	+ 10.6 - 10.6

a. Dynamic Model. A finite element dynamic model of the experiment was generated which represents the detailed design. The model contains 2915 degrees of freedom and over 1000 collocation points and elements. The model includes representations of the following experiment components:

- o Experiment base structure (pallet)
- o valve box/interface panel
- o vacuum jacket
- o girth ring
- o bipod struts
- o trunnions
- o storage tank (including VCS mass loading)
- o internal flow lines: horizontal vent  
horizontal drain  
pressurization/vent  
outflow line  
fill and drain line
- o liquid acquisition device
- o hydrostatic representation of LH2

The model is constrained at the Spacelab pallet interface with the proper boundary conditions.

A computer plot of the storage tank model is shown in Figure V-24. A by-product of the LH<sub>2</sub> hydroelastic model was definition of the LH<sub>2</sub> slosh modes. The fundamental mode was found to be 1.27 Hz in the launch configuration (> 94 percent fill).

The detail associated with the vacuum jacket model is shown in Figure V-25 and a plot of the vacuum jacket girth ring, valve box and the electronic equipment mounting plate is presented in Figure V-26. Figure V-27 shows the overall model with the vacuum jacket and storage tank not shown for clarity. The dynamic mass of the model totals 451 kg (993 lbm).

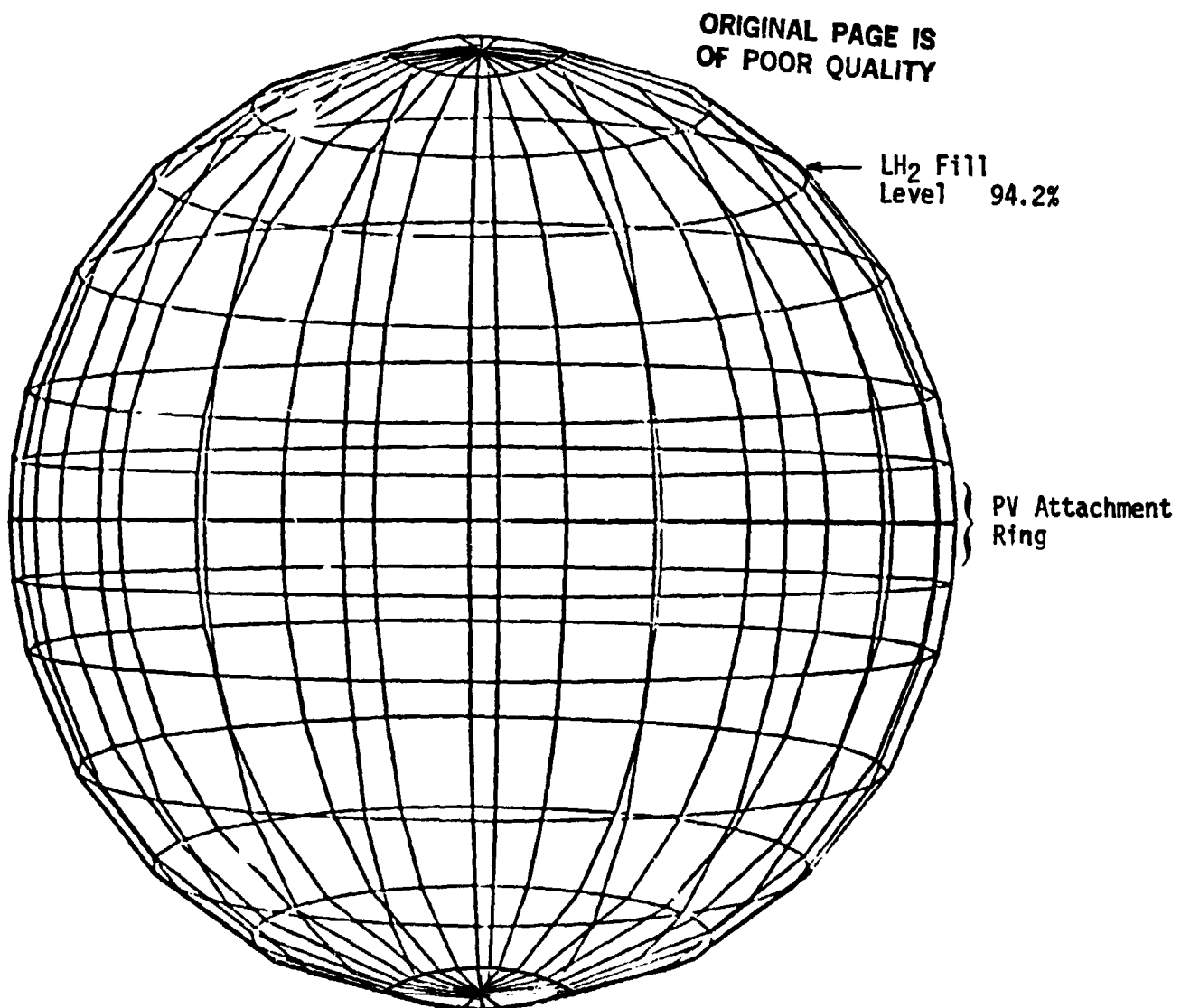


Figure V-24 Storage Tank Model

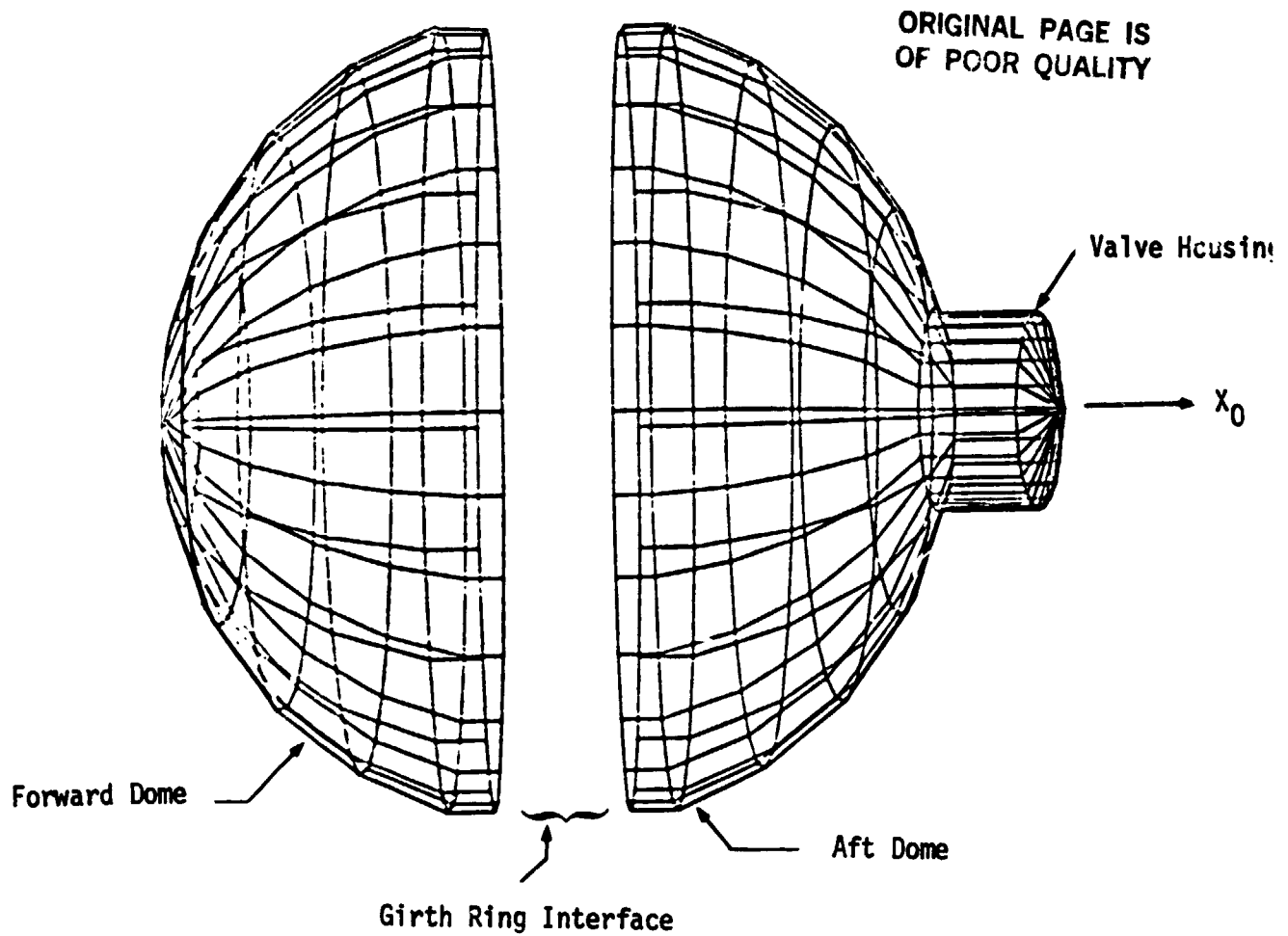


Figure V-25 Vacuum Jacket Model

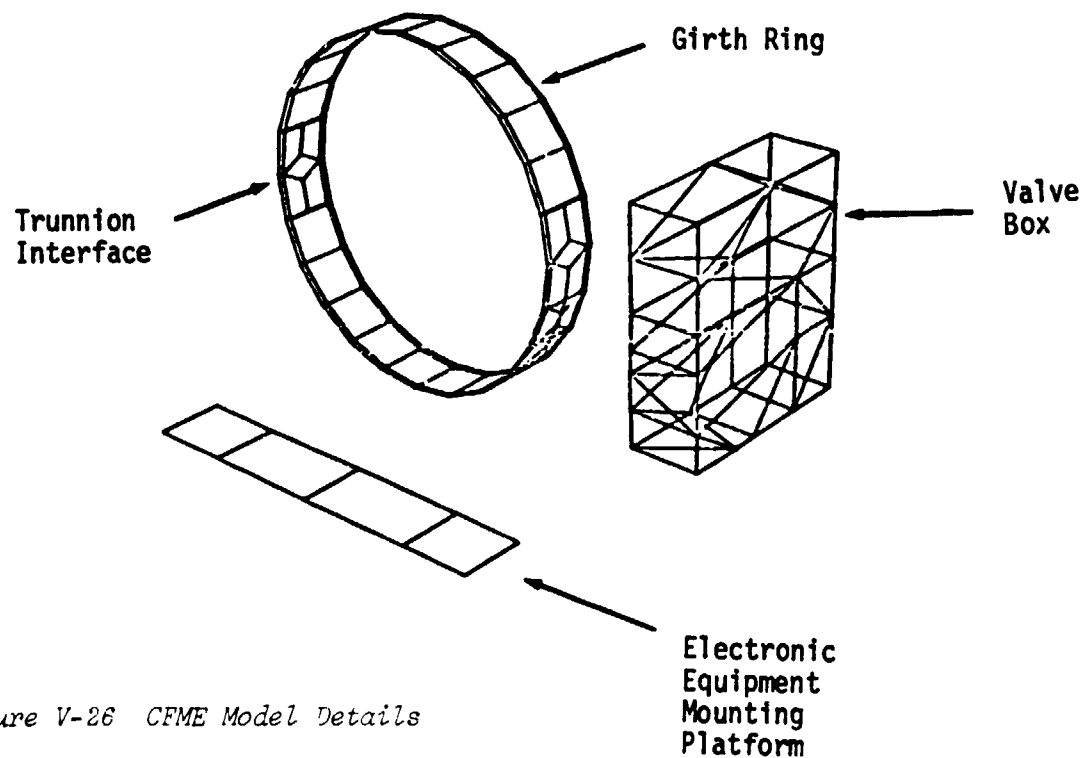


Figure V-26 CFME Model Details

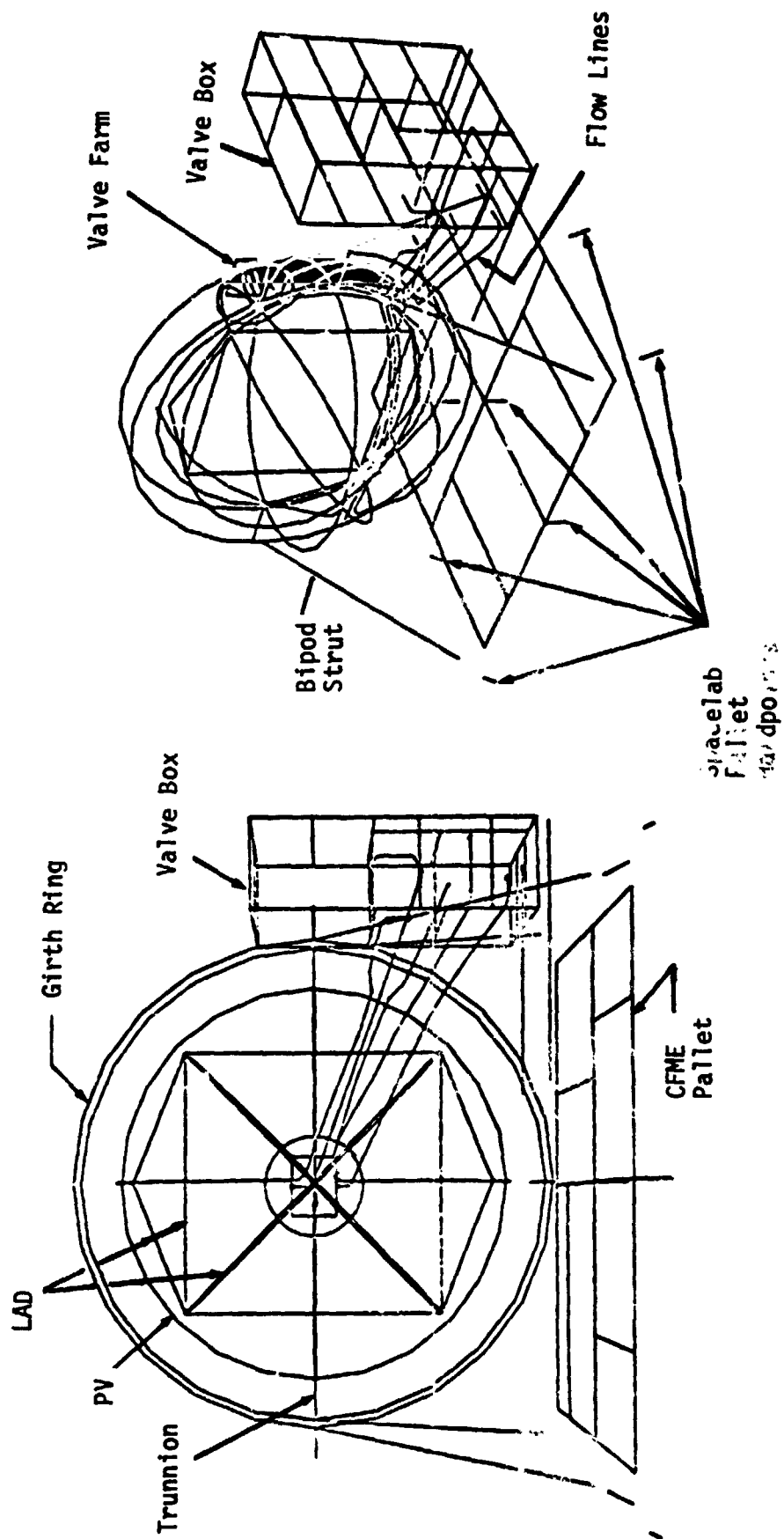


Figure V-27 CFME Dynamic Model



b. Modal Analysis Results. Frequencies of the first nineteen modes calculated from the dynamic model are listed in Table V-4. Five modes fall below the 35 Hz goal. Most of these are associated with the valve box structure. Even though the frequency criteria is not satisfied, the modal frequencies are out of the frequency range of primary Shuttle response (4-18 Hz). Due to the asymmetry of available Spacelab pallet hardpoints, meeting the 35 Hz criteria may impose an excessive weight penalty. Failure to satisfy the criteria does not imply lack of structural integrity, but only that a coupled loads analysis should be conducted to confirm structural margins.

*Table V-4 CFME Modal Frequencies*

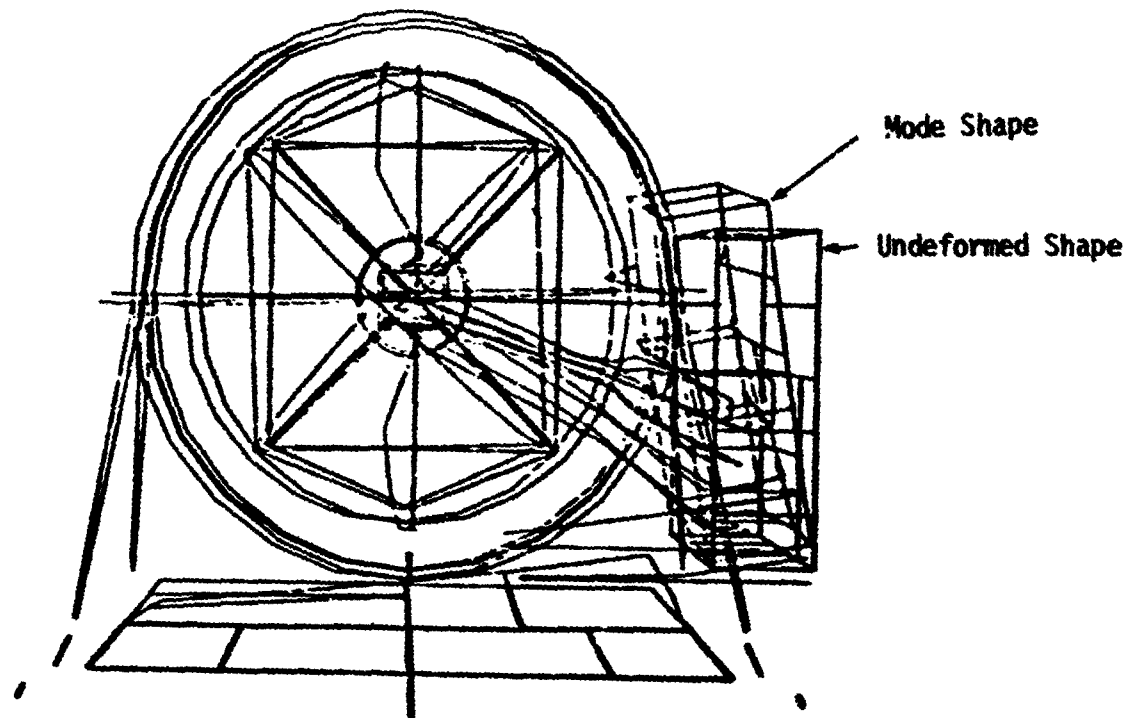
Mode	Frequency (Hz)	Mode	Frequency (Hz)
1	22.38	10	46.35
2	28.47	11	46.98
3	29.60	12	49.65
4	32.64	13	52.88
5	33.63	14	56.20
6	35.76	15	57.65
7	37.76	16	61.47
8	38.98	17	63.39
9	43.03	18	65.16
		19	68.98

Figure V-28 shows computer plots of the first two modes showing valve box and support structure motion.

c. Loads Analysis. An analysis was performed to determine member stresses and loads in the experiment due to quasi-static and random vibration loadings. The finite element dynamic model was employed in this analysis.

The quasi-static load factors, presented in Table V-3, were applied to the model in the eight possible sign perturbations. Member stresses/loads were calculated as shown in the following matrix equation.

$$(\sigma_{QS}) = \begin{bmatrix} \text{Member} \\ \text{Load/Stress} \end{bmatrix} = (LSTM)(K)^{-1}(MASS)(RBT) \begin{pmatrix} LF \\ LF^x \\ LF^y \end{pmatrix}$$



Mode 1,  $f = 22.38 \text{ Hz}$

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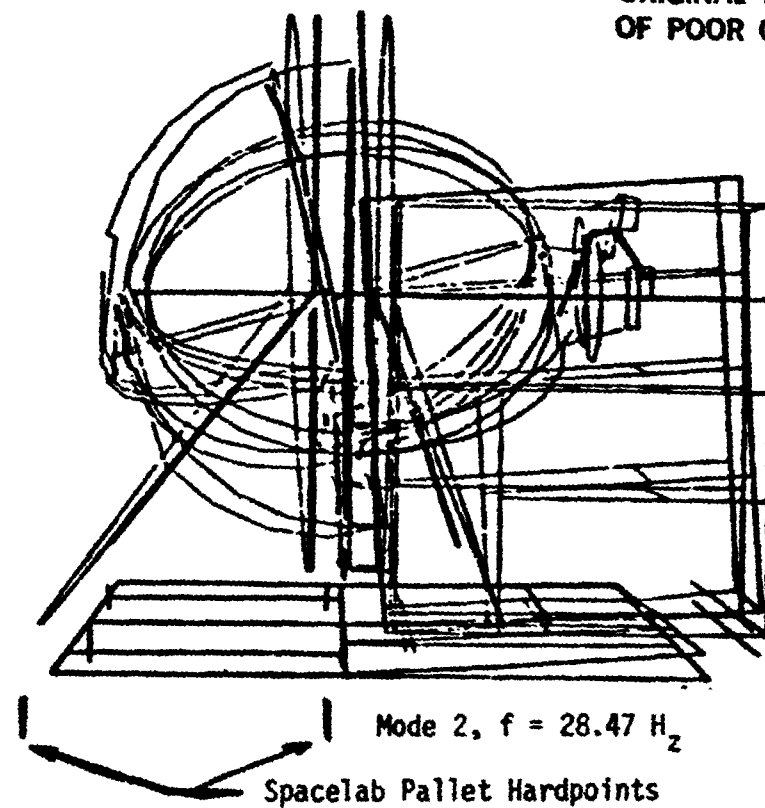


Figure V-28 CFME First and Second Mode Structural Model

Where: LSTM = member load/stress transformation matrix relating loads/stresses to deflectors,

$K^{-1}$  = model influence coefficient matrix relating deflections to applied loads,

MASS = model mass matrix,

RBT = rigid body transformation matrix,

LF = load factor vector (g).

Member loads/stresses due to the Spacelab pallet random vibration environment were also calculated. The dynamic model was analytically base-driven with the random vibration spectrum (8.72 grms) via the Thompson-Barton analysis technique (Ref. 25). This analysis resulted in three experiment deflections in each vibration mode. Member loads/stresses were calculated for each mode and root-sum-squared to arrive at the total load/stress.

$$(\sigma_R)^* = \left[ \begin{array}{c} \text{Member} \\ \text{Load/Stress} \end{array} \right]_R = \sqrt{\sum_k^{\text{modes}} \left[ (LSTM)(X_3\sigma) \right]^2}$$

\*Calculated for each axis input: X, Y, Z

The total member loads/stresses predicted during STS flight were arrived at by summing the maximum quasi-static stress in an element with the maximum random stress in an element.

$$\sigma_T = \sigma_{QS} + \sigma_R$$

Stress concentration factors were included in the detailed review of the finite element results.

3. Fatigue Analysis Methodology. The seven-mission life requirement dictated the need to consider the fatigue life of the design. The fatigue assessment was broken into two parts: 1) low frequency fatigue due to STS transient

loads, and 2) high frequency fatigue due to random vibration loads. Miner's cumulative damage theory was used to assess fatigue damage.

This theory states that fatigue damage accumulates linearly. The damage number is defined by ratioing the number of cycles at a given stress level to the allowable cycles at that stress level (based on the S-N characteristics of the material). The damage numbers for all the stress levels experienced are summed to arrive at the total damage estimate.

$$\text{Damage} = \sum_{i=1}^M \frac{n_i}{N_i} \leq 1.0$$

M = Number of Discrete Stress levels

n = Number of Cycles at Stress Level

N = Allowable Number of Cycles at Stress Level , Based on S-N Curve for Material

A damage number greater than 1.0 indicates fatigue failure. Consequently, it is desirable to have a design whose damage number falls considerably below 1.0.

a. Low Frequency Fatigue Assessment. The fatigue damage assessment due to low frequency transient loads considered the two primary loading events of liftoff and landing. Based on the Spacelab 2 Integrated Payload Requirements Document (Ref. 26), exposure times of 9 seconds and 10 seconds were assumed, respectively. A 35 Hz response frequency was assumed and a fatigue life factor of four was applied to allow for the uncertainty of the analytical technique for predicting fatigue. Hence,

$$N_{QS} = (35 \text{ Hz}) (9\text{s} + 10\text{s}) (7 \text{ missions}) (4) = 18,620 \text{ cycles}$$

The element stresses calculated in the quasi-static loads analysis were assumed to occur for this number of cycles.

b. High Frequency Fatigue Assessment. Fatigue damage due to random vibration loading was calculated from the Thompson-Barton random vibration base drive analysis. Stress statistics were calculated assuming a Rayleigh

distribution of stress peaks utilizing a method developed by Kacena and Jones (Ref. 27). An exposure time of 50 seconds + 20 seconds/mission times 7 missions, or 190 seconds, was assumed as per the Statement of Work. It should be noted that during liftoff the experiment is only subjected to 5 seconds of high frequency random loading and a fatigue life factor of four is applied to get the 20 seconds. The element damage due to low and high frequency exposure were summed to arrive at the total damage.

4. Stress Analysis. A stress analysis was performed to ensure the structural and functional integrity of the CFME system. This was largely accomplished by two analyses. One was for the storage tank with attached trunnions and the second was for the vacuum jacket, including girth ring and external support tubes. These were separated from each other because the axisymmetry of the storage tank lends itself to the Bosor4 Program (Ref. 28). Since both the structure and the loading of the storage tank are symmetric about the R and Z axis of the Bosor4 coordinate system, only a fourth of the tank need be modelled (Fig. V-29). This allowed for faster, less expensive computer runs on the storage tank system. The primary function of this Bosor4 model was to verify the interactive moment near the pressure vessel and trunnion interface. Detailed analysis of the attached trunnions will be covered in the fatigue analysis.

The vacuum jacket and components were analyzed using a Nastran Model (Ref. 29). This model consists of about 500 node points which describe the geometric configuration of the two hemispheric vacuum jackets with connecting girth ring and support tube. A total of approximately 510 plate elements were used to build the model. An iterative process on structural thickness was used in which loads were taken from the Bosor4 Computer Analysis and input into the Nastran analysis until the resulting deflections as determined from the Nastran analysis were negligible.

The LAD was also modeled using Nastran. The initial model showed the structure to be polar mounted to the inner pressure vessel at two locations. One end would be welded to the tank with the other end restrained in the lateral direction only. This however showed deflections due to torsional loads which would cripple the material. Therefore, a cross-backing structure was added midway between the two ends. This reduced torsional loads and solved deflection problems.

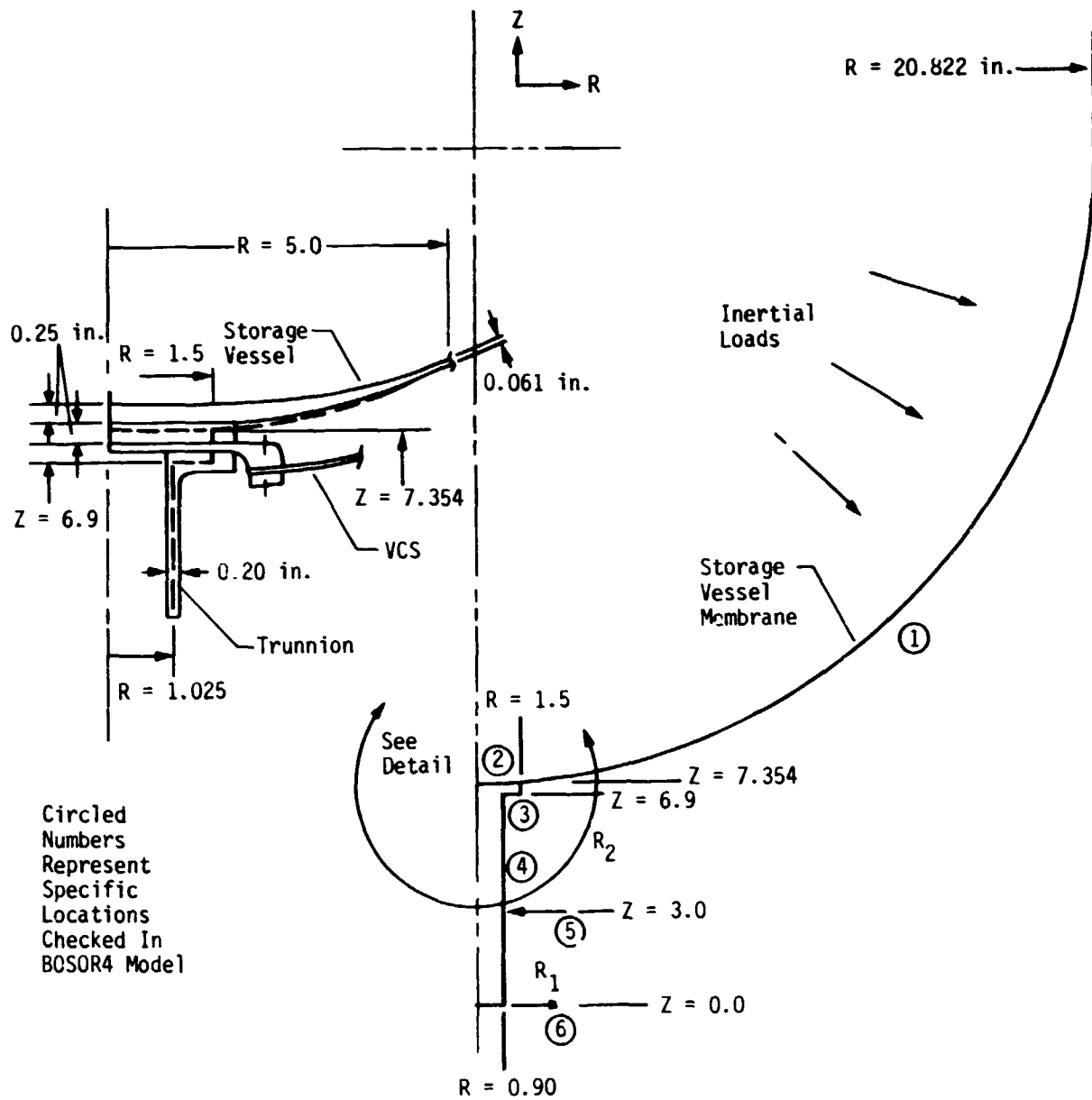


Figure V-29 CFME Storage Tank/Trunnion Idealization

After the preliminary design review, there were some changes to the design criteria. Loads were updated, a fatigue requirement of seven missions was added, and deflections due to the pallet interface with the cargo bay were imposed. From these requirements, additional analysis was done and a detailed design was arrived at for final analysis. This analysis included updating the results from the three computer models. It also involved an additional Nastran model to input deflections into the CFME pallet. Hand analysis was then used along with results from the Nastran model to analyze pallet hardpoints.

Hand analysis was also used on numerous other components. The vapor-cooled shield, ground support equipment, valve panel, and trunnions were all analyzed using hand methods.

In addition, a fatigue analysis was performed on all components. This analysis was patterned after the MFSC Spacelab 1 and 2 fatigue analyses. This combined a random loading spectrum with quasi-static loads using the following equation:

$$\sigma_{EQ} = \frac{\sigma_{HC}}{1 - \frac{\sigma_{LC}}{F_{TU}}}$$

$\sigma_{EQ}$	=	Goodman Equivalent Stress
$\sigma_{HC}$	=	Stress Due to Random Loading
$\sigma_{LC}$	=	Stress Due to Quasi-Static Loading
$F_{TU}$	=	Material Ultimate Tensile Strength

The cumulative damage number defined previously is then calculated using Miner's theory.

All components proved structurally sound in fatigue except the trunnions. The trunnions are formed of composite material made up of alternating layers of S-glass. Material allowables for the laminate were generated by a computer program, SQ5 (Ref. 30). This stress value was used with a S-N curve and an acceptable cumulative damage was calculated (Fig. V-30).

Upon completion of the updated stress analysis, a final dynamic model of the entire system was generated to substantiate loads and stresses. From previous analysis, a few critical areas were picked to re-analyze. All areas still showed positive margins of safety or acceptable cumulative damage except for the horizontal vent line as indicated by the minimum margins of safety listed in Table V-5. When the design is updated, an improvement in the means of supporting the vent lines will be required. Final proof of the design will come with the implementation of the component and system level tests.

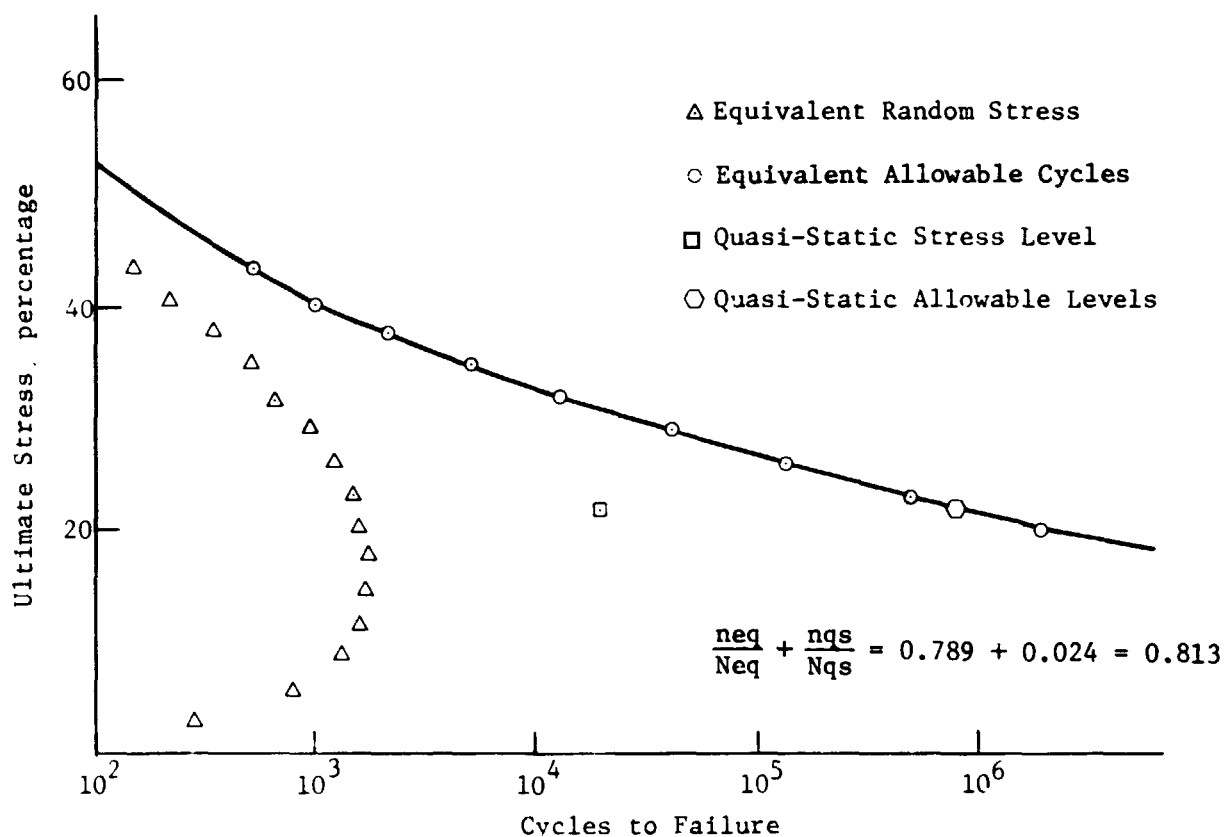


Figure V-30 Trunnion Laminate Composite S/N Curve



Table V-5 Minimum Margins of Safety

System Component	Critical Load	Mode of Failure	M.S.
LAD	50 g	Bending	+0.07
Storage Tank	Ult. Pressure at Room Temp.	Burst	+0.04
Vacuum Jacket	Ult. External Pressure	Collapse	+0.21
Bi-Pod Support Tubes	Inertial Loads	Compressive Buckling	+0.02
Horizontal Vent Line	Inertial Loads	Combined Axial and Bending	-0.74
Trunnion	Inertial Loads	Fatigue	0.813*
Pallet	Inertial Loads	Crippling	+0.40
Helium Tank Straps	Expansion due to Tank Pressurization	Tension	+0.94
Vertical Sling (GSE)	Inertial Loads	Bending	+0.01

\*Damage number rather than margin of safety

## VI. GROUND TEST PROGRAM

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The ground test program consists of inspections and tests to verify integrity of the liquid hydrogen tank assembly, pressurization system, Data Acquisition and Control System (DACS), and all associated components, instrumentation, plumbing and wiring contained on the CFME pallet. In-line testing of portions of the tank assembly and the DACS are conducted to provide early confidence of functional integrity. Figure VI-1 presents a flow chart of the in-line, functional, environmental, post-test functional tests and inspections, and gives the test sequence. These tests will verify that the CFME flight hardware conforms to the requirements as specified in the contract Statement-of-Work and is free of manufacturing defects.

In-line tests consist of component and subassembly tests which are performed at key points in the fabrication sequence to verify hardware integrity before performing steps that would preclude efficient repair or replacement. Tests are performed on the component level, as required, in order to verify compliance with design requirements and for the purpose of certifying components for use. Whenever possible, off-the-shelf components were selected which met design requirements and needed no further vendor or Martin Marietta testing. Temperature sensors, pressure transducers, liquid sensors, flow meters and mass meters will be received from the vendors with valid calibrations or will be calibrated before being installed in the CFME. Functional tests verify that the CFME is operating as designed with respect to items such as control logic, valve operation, instrumentation, GSE control, pressure integrity, thermal control, outflow and abort considerations. They also verify the acceptability of procedures for loading, pressurizing, off-loading, and inerting of the CFME.

Off-design performance tests will establish the operational characteristics of the CFME when operating within the extremes of voltage fluctuations, and will verify that no hazardous conditions or failures result from operating at the high and low extremes of DC voltage. The environmental test series will verify the operation of CFME systems when subjected to simulated electromagnetic vibration and thermal environments.

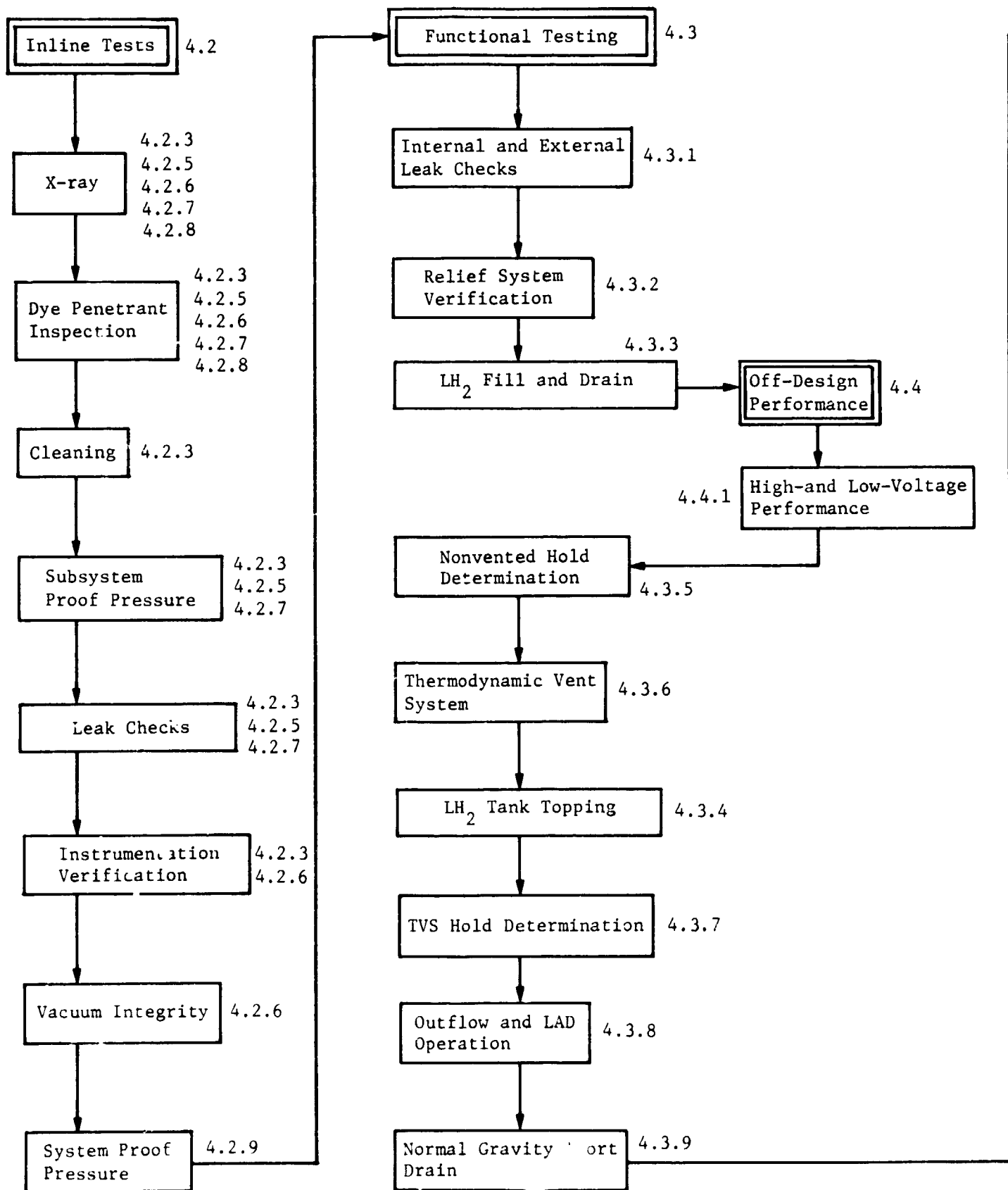
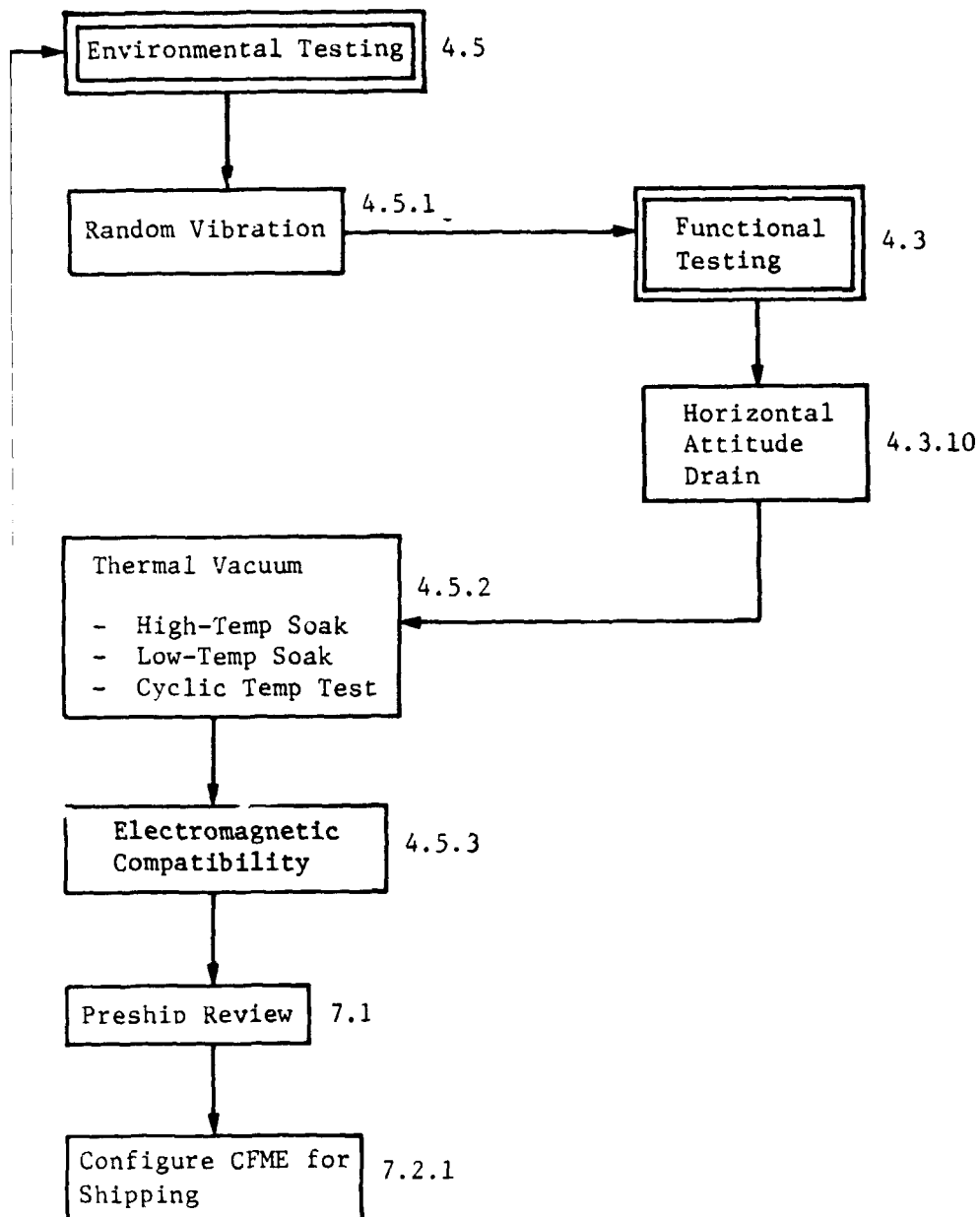


Figure VI-1 CFME Ground Test Flow Chart



Note:  
Numbers outside test blocks  
refer to paragraphs in the  
ground test plan (Ref 11)

The CFME ground test program includes the building and testing of a dedicated test article, designated as the CFME-TA. This test article contains all of the CFME systems required to prove out the CFME system design, and will undergo a series of tests similar to that of the flight article.

#### A. Component Tests.

Specific CFME component tests have been defined for design items which require early verification due to the critical application of the item and/or a lack of a sufficient data base exists for having minimum risk in the normal series of ground tests.

1. Liquid Hydrogen Tank Burst and Cycle Test. This test verifies the integrity of the pressure vessel design to withstand the pressure cycles which will be encountered throughout a seven mission life, demonstrates the minimum baseline burst pressure limit of  $1550 \text{ kN/m}^2$  (225 psig), and demonstrates the adequacy of fabrication and assembly techniques. Details of the test plan are provided in Reference 13. The liquid hydrogen tank test article will be built to the requirements specified in Martin Marietta Drawing 849CFME1038, with the following qualifications:

- o The liquid acquisition device will not be installed.
- o All tank penetrations will be included. An inlet and an outflow tube will be located on the vertical axis at opposite ends of the tank (normal outflow and vent penetrations). All other penetrations will be capped.
- o Instrumentation will be limited to the requirements as specified in the test plan (Ref. 13).
- o The test article will not contain a vacuum jacket, thermodynamic vent system, or vapor-cooled shield.

The test article will be supported during the test by simulated trunnion support members similar in configuration to the selected flight design which supports the hydrogen storage vessel within the vacuum jacket.

In order to gain an insight into tank deformation during the burst pressure test, three strain gages will be installed. One will be located on the tank interior (installed before the attachment ring welds are made) and two on the tank exterior. Sensors will be installed in an area away from the ring where shell wall thickness is uniform and of minimum value. The two externally mounted sensors will be located on opposite sides from one another while the one on the inside will be mounted beneath and perpendicular to one on the exterior. Sufficient pressure data can be obtained from ground support equipment measuring devices.

A hydrostatic proof pressure test of  $827 \pm 10 \text{ kN/m}^2$  ( $120 \pm 1.5 \text{ psia}$ ) will be performed on the completed article. Once the proof pressure level has been achieved and maintained for two minutes, the tank pressure will be reduced. No deformation or permanent set is allowed. Fluid will be left in the tank for the pressure cycle and burst test. This test will be performed twice since the CFME flight tank is scheduled to undergo an in-line and a system proof pressure test. The pressure test verifies the capability of the tank design to withstand the pressure cycles which will be encountered throughout a seven mission life and conditionally qualifies the tank design for use on the CFME. The maximum expected number of pressure cycles projected over the life of the experiment is as follows:

	Number of Cycles	Pressure Level	
		$\text{kN/m}^2$	(psia)
Proof Tests	2	827	(120)
Acceptance Tests	8	413	(60)
Functional Tests	10	413	(60)
Performance Tests	5	413	(60)
Environmental Tests	5	413	(60)
Preflight Checkout	35	413	(60)
Flight	35	413	(60)
Total Cycles	100		

Document NHB 1700.7, Paragraph 208.4, specifies that pressure vessels shall be qualification tested to demonstrate a life cycle capability of at least twice the maximum predicted number of operating cycles. Therefore, the

number of pressure cycles to which the test article will be subjected is 200 cycles. Four of these cycles will be at  $827 \text{ kN/m}^2$  (120 psia) and the remainder at  $413 \text{ kN/m}^2$  (60 psia).

The burst pressure test will demonstrate no failure at the design burst level of  $1550 \pm 10 \text{ kN/m}^2$  ( $225 \pm 1.5$  psia), and will complete the qualification of the tank design for use on the CFME. The test article will be stabilized at ambient temperature and then hydrostatically pressurized at a uniform rate of  $207 \text{ kN/m}^2/\text{min}$  (30 psi/min) to  $1550 \pm 10 \text{ kN/m}^2$  ( $225 \pm 1.5$  psia). Once the burst pressure level is achieved and maintained for two minutes, tank pressure will be reduced. The test will verify that the test article will not rupture below the burst pressure of  $1550 \text{ kN/m}^2$  (225 psia), which is 3.75 times the design operating pressure of  $413 \text{ kN/m}^2$  (60 psia).

2. Trunnion Tests. The purpose of the CFME trunnion tests is to evaluate the capability of the trunnion design to withstand the expected extremes of vibration and loading which will be encountered throughout a seven mission life cycle. Details of the trunnion tests are contained in Reference 14.

The capability of the CFME to meet the seven mission requirement is extremely sensitive to the fatigue life of the composite trunnions at cryogenic temperatures. Because of the limited extent of analytical or experimental investigations of the fatigue life of composites at cryogenic temperatures, an early verification of design and performance capability is desired. This series of component tests is designed to evaluate the integrity of the trunnion design prior to the fabrication and assembly of the flight hardware trunnions. Results obtained from these tests, when combined with data obtained from trunnion-mounted instrumentation on the CFME-TA, will qualify the trunnion design for use on the CFME.

The need for performing lamina and laminate mechanical property tests is justified on the basis of the following considerations:

- o A lamina and laminate mechanical property data base makes possible a systematic redesign of the trunnion should the initial design fail to meet all established requirements.

- o Non-standardized layup techniques and testing methods limit the applicability of mechanical property data for S-glass/epoxy composites which have been generated by other investigators. This requires the establishment of a data base from test specimens which have been fabricated such that the materials and layup techniques used for trunnion fabrication are duplicated as closely as possible.

a. Lamina and Laminate Mechanical Property Tests. The objective of these tests is to generate baseline mechanical property data for multilayer lamina material, which will be used in the fabrication of the trunnions, and for laminate material, which approximates the layup configuration of the completed trunnions.

The cured lamina test material, consisting of ten layers of unidirectional S-glass roving in an epoxy resin matrix (total lamina thickness of approximately 0.09-in), and the laminate test material, consisting of multiple layers of S-glass roving and style 181 E-glass cloth (total laminate thickness of approximately 0.2-in) will be tested. Tensile tests will be performed on the lamina and laminate materials at room temperature and in liquid nitrogen and liquid hydrogen. Room temperature and cryogenic test specimens will be pin-loaded through a pair of clamping jaws. Cryogenic tests will be performed in a cryostat, with the specimens totally submerged in the cryogenic liquid. Compression tests on the lamina and laminate specimens will be performed at room temperature and in liquid nitrogen.

Fatigue tests will be performed on the laminate material at room temperature, and in liquid nitrogen and liquid hydrogen. In order to provide comparison data, both tension-tension ( $R = 0.05$ ) and tension-compression ( $R = -1$ ) fatigue tests will be performed at room temperature and in liquid nitrogen (where  $R = \text{minimum stress}/\text{maximum stress}$ ). Only tension-compression tests will be performed in liquid hydrogen. The tension-tension and tension-compression tests use a honeycomb specimen made from two layers of laminate material bonded to a low-density honeycomb core. The honeycomb core is designed to prevent buckling of the laminate material during the compression half of the loading cycle, while not contributing significantly to the



laminate strength. All specimens will be pin-loaded through clamping jaws, with the cryogenic tests performed in a cryostat. Specimen loading will be accomplished using an MTS servohydraulic testing machine.

b. Structural Integrity Tests. The purpose of these tests is to check the structural integrity of the trunnions to be used on the CFME tank. Test specimens will consist of fifteen trunnions manufactured according to drawing numbers 849CFME1035 (fixed trunnion) and 849CFME1036 (floating trunnion).

The structural tests proposed in Reference 14 for a thorough characterization of the structural capabilities of the trunnions include axial tension, bending only, combined bending and axial loading, combined axial compression and bending, and fatigue under the critical loading conditions resulting from the other specific loading tests. All tests will be run at room temperature except the axial fatigue tests, which will be run in liquid nitrogen. Specimens to be tested statically will have the load applied gradually until failure occurs. A loading spectrum will be applied to the trunnions to be fatigue tested. Several specimens will be cycled to failure while several others will be cycled per the loading spectrum to 20,000 cycles and then statically tested in the critical combined axial and bending condition. Strain data will be recorded in axial and radial directions during both the fatigue and static load tests.

c. Dynamic Impact Test. The objective of this test is to determine the capability of the trunnion/trunnion support tube/girth ring interface to withstand random vibration impact dynamics. Due to manufacturing tolerances and thermal contraction, a gap will exist between the trunnion and support tube at the mid-trunnion support ring. During launch, random vibration excitation will cause the trunnion and support tube to "chatter" and impact at this interface. This may cause structural degradation of the trunnion. The proposed test will simulate this impact loading.

The trunnions will be mounted in a test fixture which simulates the support tube interface of the flight hardware. A "gap" at the middle trunnion support ring will be selected (and designed in), based on predictions for the launch condition, and accounting for manufacturing tolerances and thermal

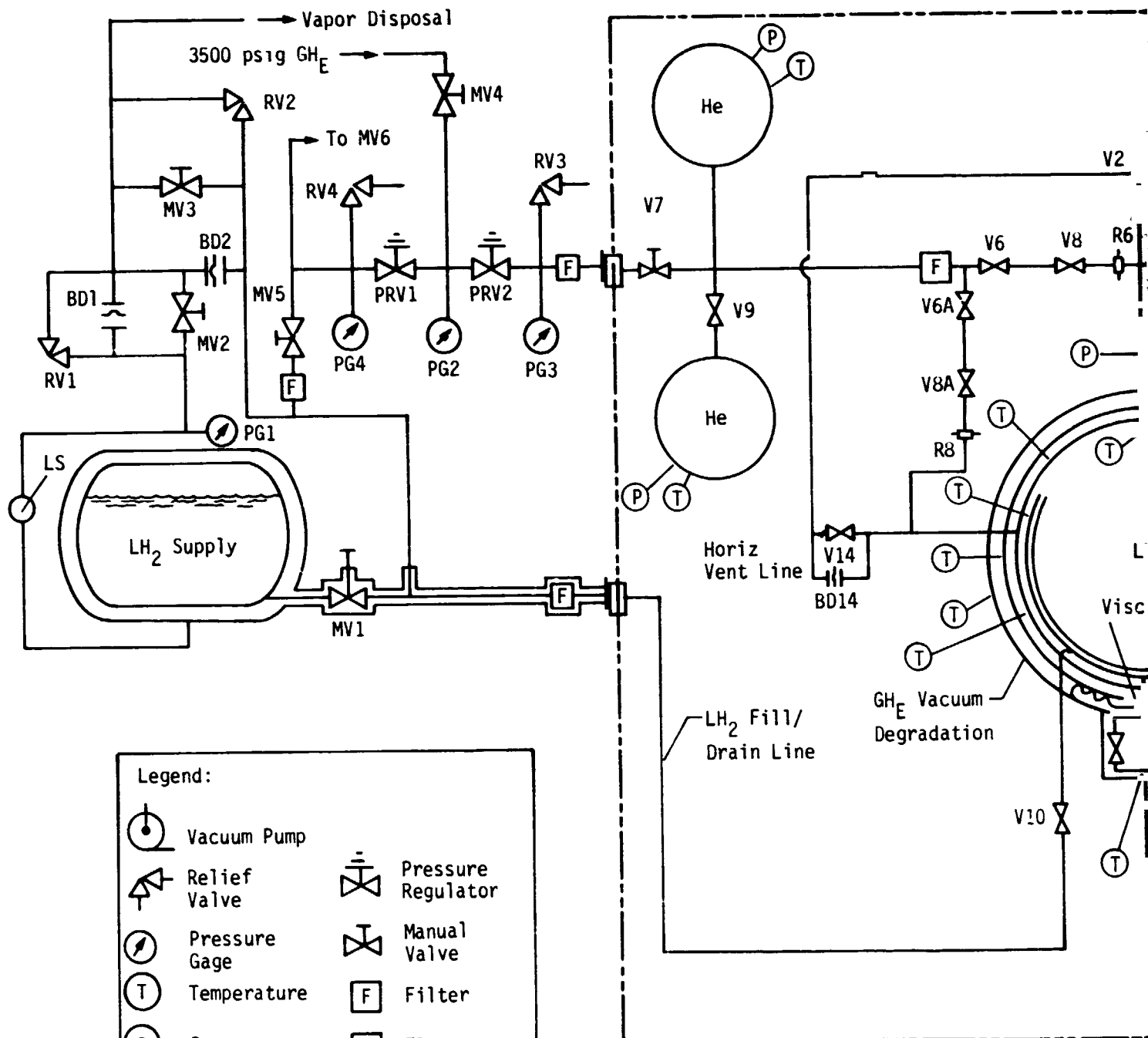
contraction of the trunnion. The test will be run with the trunnion supporting ring at the predicted launch temperature. Current predictions show this temperature near the outer edge of the ring to be close to ambient, 21°C (70°F).

#### B. CFME-TA Tests.

The Cryogenic Fluid Management Experiment Test Article (CFME-TA) consists of the systems necessary to support qualification testing of the CFME Tank assembly on the experiment pallet. In addition to the tank and its supports, all lines from the tank assembly to the valve panel, along with interface mounts and support structure, will be provided. Safety related valves and burst discs are also a part of the CFME-TA design. A schematic of the CFME-TA appears in Figure VI-2. Details of the CFME-TA tests are contained in the test plan, Reference 15.

The CFME-TA tests consist of inspections and tests to verify integrity of the liquid hydrogen tank assembly, all associated components, instrumentation, plumbing and wiring contained on the CFME-TA pallet. In-line testing of portions of the tank assembly will be conducted to provide early confidence of functional integrity. Figure VI-3 presents a flow chart of the in-line, functional, and environmental tests and inspections, gives the test sequence, and lists the appropriate paragraph of the CFME-TA Test Plan where a more detailed discussion is available. These tests will verify that the CFME-TA conforms to the performance requirements and is free of manufacturing defects.

1. In-line Tests. In-line tests consist of component and subassembly tests which are performed at key points in the subassembly sequence to verify hardware integrity before performing steps that would preclude efficient repair or replacement. Tests are performed on the component level, as required, in order to verify compliance with design requirements and for the purpose of certifying components for use. Temperature sensors, pressure transducers, liquid level sensors, flow meters and mass meters will be received from the vendors with valid calibrations or will be calibrated before being installed in the CFME-TA.



Legend:

	Vacuum Pump		Pressure Regulator
	Relief Valve		Manual Valve
	Pressure Gage		Filter
	Temperature		Flowmeter
	Pressure		Mass Meter
	Control		Orifice
	Wattmeter		Disconnect
	Solenoid Valve		Level Sensor
	Burst Disc		
	Pumpout/Relief Valve		

**BOLDOUT FRAME**

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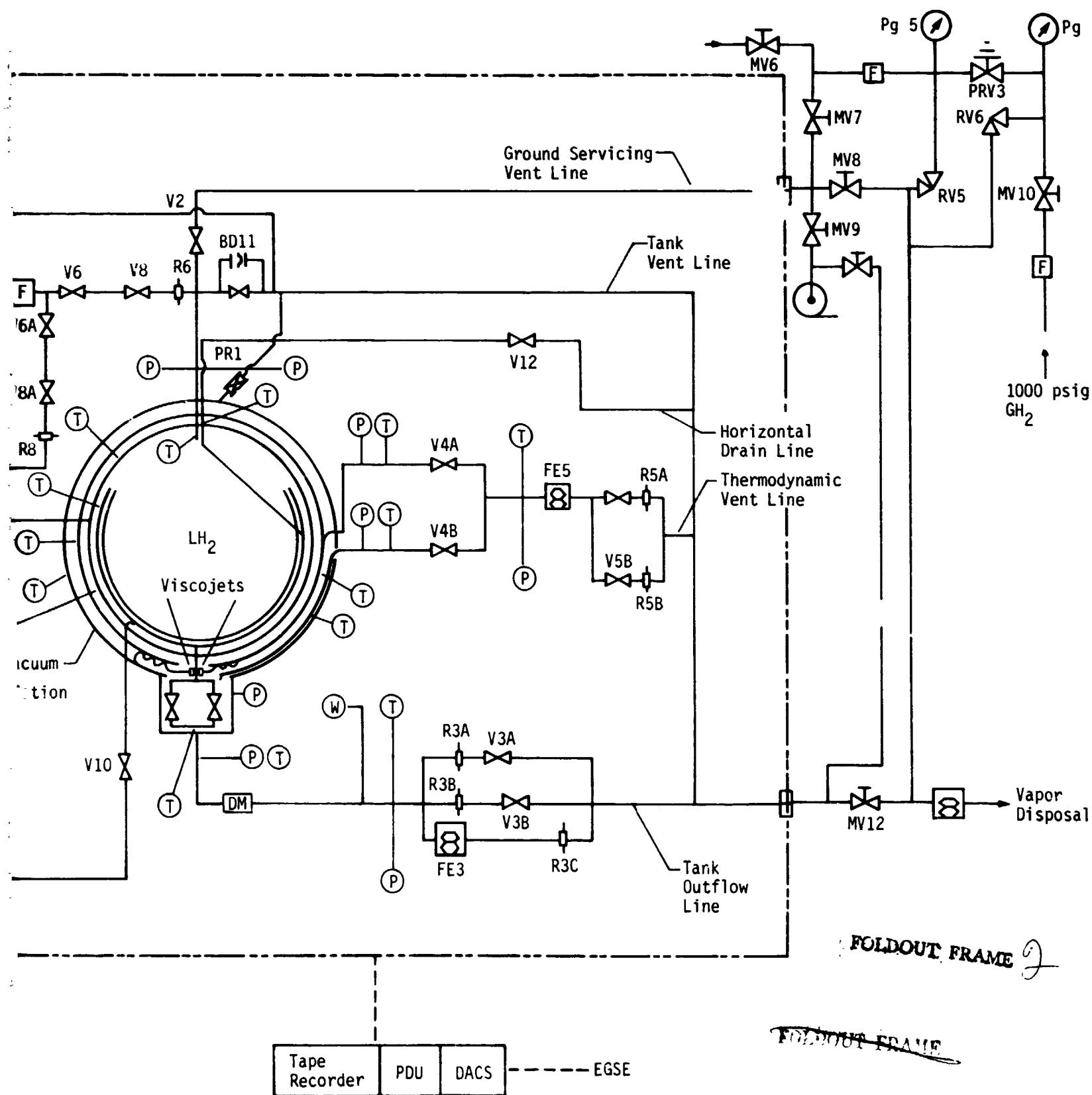


Figure VI-4 CFME-TA/Ground Test Support Equipment Schematic

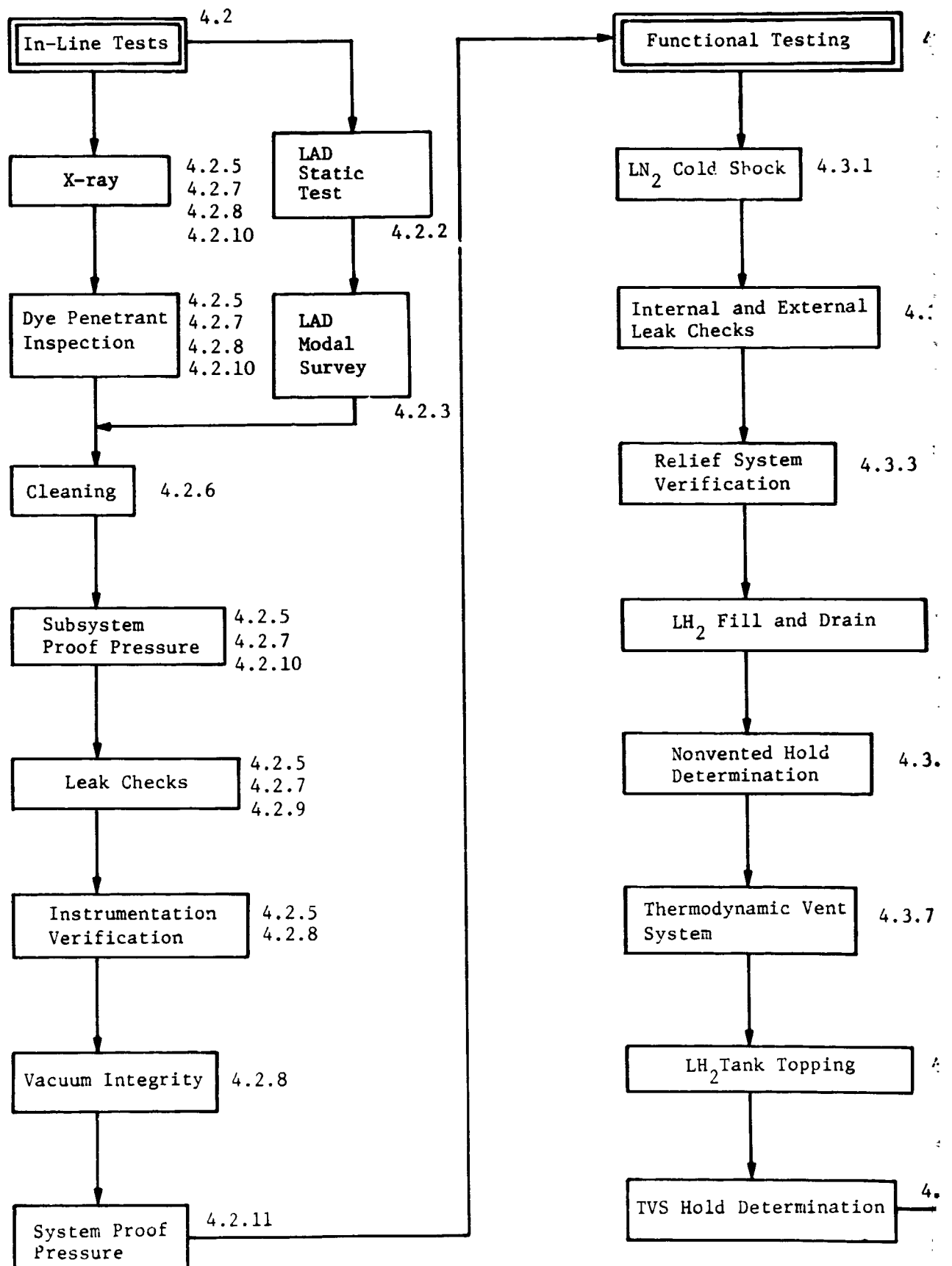
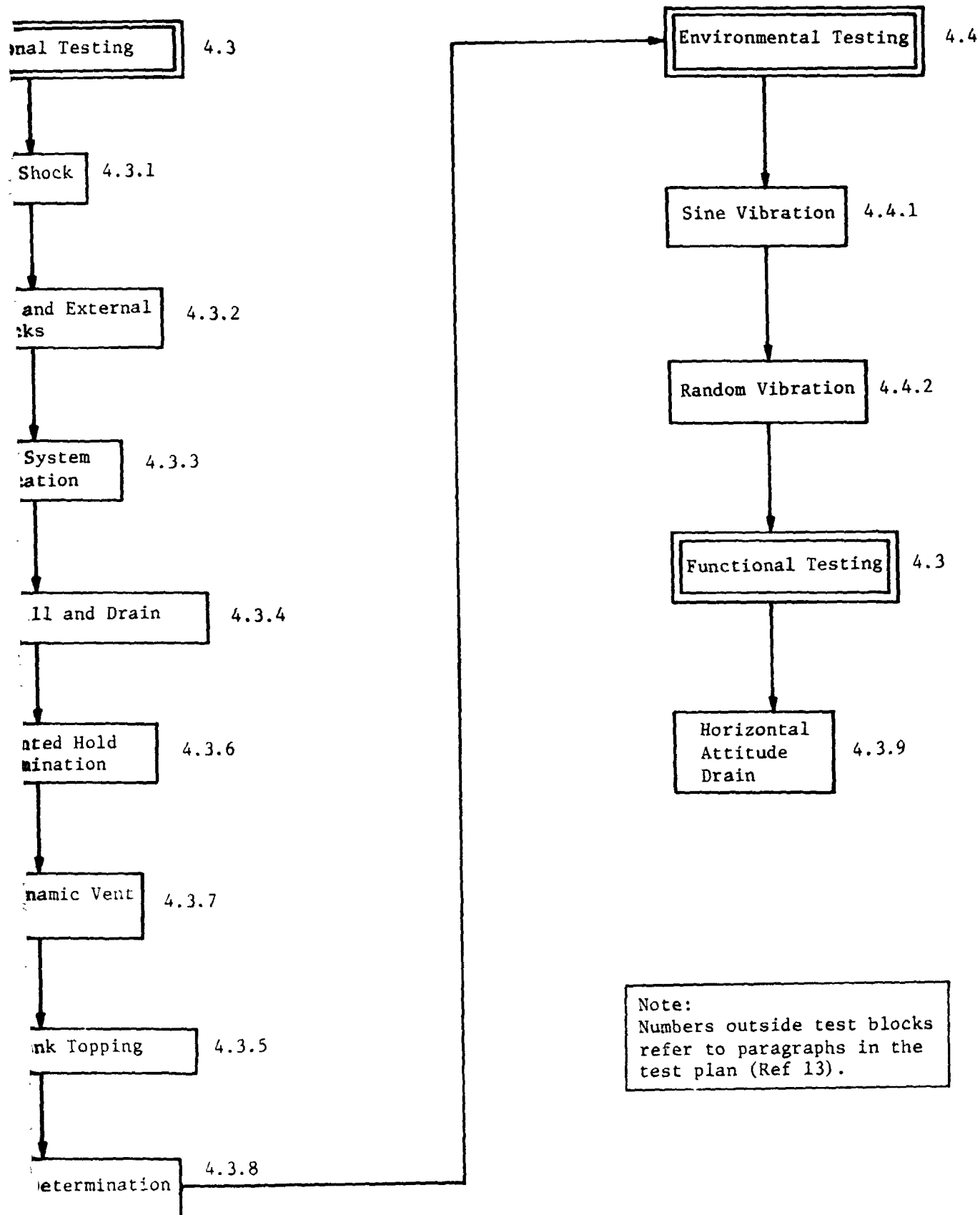


Figure VI-3 CFME-TA Ground Test Flow Chart

FOLDOUT FRAME



a. Liquid Acquisition Device Performance Test. The following tests will be performed on the LAD during various stages of the manufacturing process:

- o Cleaning of the screen material and channels before assembly.
- o Bubble point verification of the screen material before assembly.
- o Cleaning of the LAD after assembly but prior to installation into the liquid hydrogen tank.
- o Bubble point verification of the LAD prior to assembly into the liquid hydrogen tank.

b. Liquid Acquisition Device Static Test. This test provides deflection data which can be compared with values calculated using the finite element model. Deflections will be measured for selected point loading conditions, and stress values will be obtained. Each loading condition will be applied in four incremental steps (25, 50, 75, and 100 percent of full load). Lead shot will be used to apply the load in the specified increments. All strain gage readings will be recorded at each increment of loading. Only those deflections in the direction of the applied load need to be measured. The CFME-TA liquid acquisition device will be used for these tests.

c. Liquid Acquisition Device Modal Survey. This test validates the dynamic model of the LAD by measuring modal characteristics (mode shapes, frequencies, damping) below 70 Hz. The LAD will be mounted in a tool, with tool/LAD interfaces representative of LAD/hydrogen storage tank interfaces. The tool will be "rigid" to the extent required, such that its flexibility will not influence the test results. Prior to testing, the LAD will be weighed for validation of the analytical mass matrix. Small (25 lb) electromagnetic shakers will be used to excite the structure in its natural modes of vibration. The shakers will be hung by cables providing a low frequency (1 Hz) support. The shakers will be attached to the LAD through stringer/force gage assemblies. Shaker locations will be varied during the test, in order to adequately excite the modes of interest. A pretest analysis will be used to determine initial shaker locations.

The test will be conducted using the HP5451C modal analysis system. Due to the experimental nature of this test, definitive procedures are not possible. However, the following paragraphs describe, in general, the test methods.

- o Data Acquisition - Data will be acquired up to a frequency of 100 Hz by either of two conventional methods, Single Point Random (SPR) or Multiple Point Sinewave (MPS). SPR will be used initially to determine modal parameters. MPS methods will be used where SPR is found to be inadequate.
- o Data Reduction - Modal parameters from significant modes below a frequency of 70 Hz will be extracted from the data acquired above, and presented in the form of mode shapes, frequencies, and damping.
- o Orthogonality - Orthogonality of the measured modes (with respect to the analytical mass matrix) will be assessed to determine their purity and validity. A maximum coupling, between modes, of 10 percent will be a goal for this modal survey.

d. Liquid Hydrogen Storage Tank. The following tests will be performed on the storage tank during various stages of assembly:

- o Cleaning of the tank shells after fabrication.
- o Verification of the storage tank internal instrumentation before making the closure welds, including continuity and resistance checks.
- o X-Ray and dye penetrant inspection of the closure welds.
- o Leak test of the storage tank, including a CEC Mass Spectrometer leak check.
- o Proof pressure test of the storage vessel using Freon PCA.

e. Cleanliness. The liquid hydrogen storage vessel will be flushed with Freon PCA through all flow paths after the vessel proof pressure test is complete. Samples of the flush fluid will be withdrawn from each port for particle count analysis. The maximum allowable number of particles per square foot of surface area shall be as follows:



Over 100 microns	- none
51 - 100 microns	- 5 (no metallics over 50 microns)
26 - 50 microns	- 50
11 - 25 microns	- 200
5 - 10 microns	- 1200

Previous experience with flight hardware has shown that these cleanliness levels do not introduce flow degradation of the fine-mesh screen.

f. Vapor-Cooled Shield. The VCS shall undergo the following tests during its installation on the storage vessel:

- o Proof pressure and cleaning of the TVS tubing and Viscojet valve assembly before installation to the VCS shells.
- o Cleaning of the VCS shells.
- o X-Ray and dye penetrant inspection of the TVS welds.
- o CEC Mass Spectrometer Leak Check of the TVS welds.

g. Vacuum Jacket and Girth Ring. The following tests will be performed on the vacuum jacket and girth ring as part of the fabrication process:

- o Cleaning of the vacuum jacket and girth ring.
- o Verification of the VJ and VCS instrumentation prior to making the closure welds.
- o X-Ray and dye penetrant inspections of the vacuum jacket and girth ring welds.
- o Vacuum integrity test of the completed tank assembly before installation onto the CFME experiment pallet.
- o Instrumentation verification of the completed tank assembly.

h. GHe Pressurization System and CFME Valve Panel Interface. The following tests will be performed as subsystem installation onto the CFME mounting pallet progresses.

- o Cleaning of the tubing, helium pressure vessels, valves, transducers, and other components.
- o X-ray and dye penetrant inspections of all welds.

- o Leak and proof pressure tests of tanks, lines and components, including CEC Mass Spectrometer leak check.

i. Structure. All structural welds determined to be areas of high stress will be dye penetrant inspected and x-rayed. Low stress welds will be dye penetrant inspected only.

j. System Proof Pressure Test. After the CFME-TA is totally assembled and all in-line tests are complete, a final proof pressure test will be performed using GHe. The system, including all vent system plumbing, will be pressurized to  $827 \text{ kN/m}^2$  (120 psia). Rupture of burst discs BD11 and BD14 will be prevented by maintaining a maximum delta pressure of  $67 \text{ kN/m}^2$  (10 psi) across the discs. This test will be performed as the last in-line test.

2. Functional Tests. Functional tests are defined as those tests which verify that the CFME-TA is operating as designed with respect to items such as control logic, valve operation, instrumentation, GSE control and pressure integrity (no leaks). The CFME-TA functional tests are discussed below.

a. Liquid Nitrogen Cold Shock. This test subjects the CFME-TA tank assembly to an inert cryogen prior to introducing liquid hydrogen. The CFME-TA will be installed in the vertical position in the cryogenic test cell where connections will be made to the EGSE, GHe facility pressure, and liquid nitrogen fill and vent GSE. Verification that the system moisture content is less than 10 PPM will be accomplished prior to filling with liquid nitrogen. After loading the tank assembly with liquid nitrogen, the TVS and outflow systems will be activated over an eight-hour period, and the tank then drained prior to warmup and inerting with gaseous helium. This test will be performed prior to the insulation of the valve panel tubing. The CFME-TA shall function satisfactorily over the liquid nitrogen temperature range and shall show no visible indications of structural damage, degradation or permanent set as a result of the liquid nitrogen cold shock.

b. Internal and External Leakage. This test demonstrates the pressure integrity of the CFME-TA, and verifies proper valve functioning and pressure transducer indications. The loading of the helium pressurization spheres will also be verified. The CFME-TA will be installed in the horizontal attitude in the cryogenic test cell. Internal valve poppet leakage will be checked using a CEC Mass Spectrometer with the system pressurized with gaseous helium. After each individual valve is checked, the system will be taken to operating pressure and an external CEC sniff made on all joints and connections. This test will be performed prior to the insulation of the valve panel tubing. Leakage (both internal and external) shall not exceed  $1 \times 10^{-6}$  scc/sec.

c. Relief System Verification. This test verifies the capability of the DACS system to properly operate valves V11 and V14 in order to maintain LH2 tank pressure. The CFME-TA helium spheres will have been pressurized to  $21600 \text{ kN/m}^2$  (3135 psia) and the rest of the system will be at  $386 \text{ kN/m}^2$  (56 psia) at the termination of the external CEC Mass Spectrometer leak check. This provides a convenient starting point for the relief system verification.

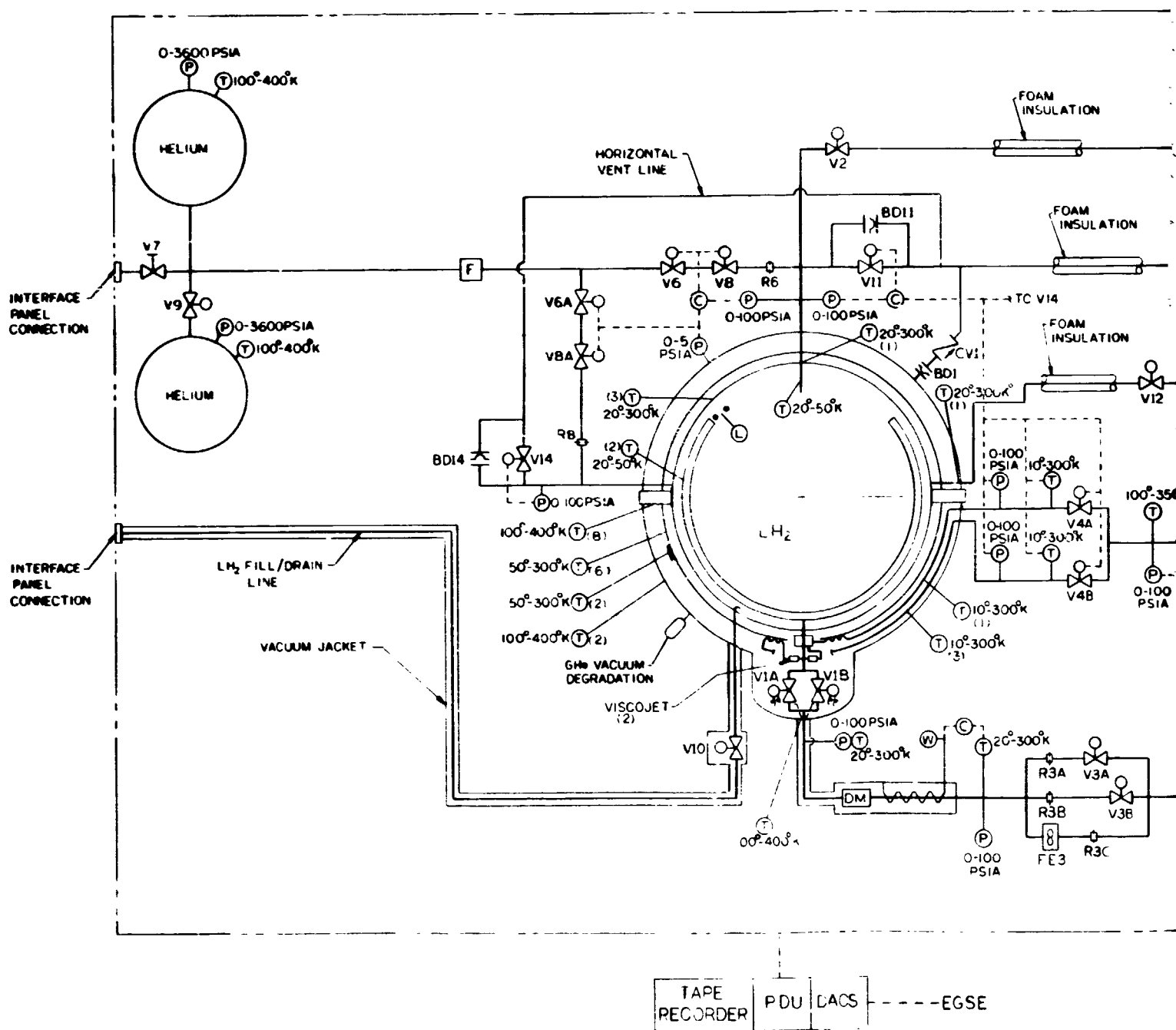
Both the horizontal and vertical relief systems will be checked separately, with the control system active for one while the other is inhibited. The first portion of this test will be to try to overpressurize the LH2 tank while monitoring LH2 tank pressure in order to determine effective operation of V11. Valves V6 and V8 will both be opened to demonstrate the operation of V11 and R6 in controlling LH2 tank pressure. The last part of this test will be to try to overpressurize the LH2 tank and determine operation of V14. Valves V6A and V8A will both be opened to demonstrate the operation of V14 and R8 in controlling LH2 tank pressure. The LH2 tank pressure shall not exceed  $413 \text{ kN/m}^2$  (60 psia) during this test. Avoiding LH2 tank overpressurization is the prime concern during this test. Emergency tank venting can be accomplished by opening valves V2, V10, or V12. Burst discs BD11 and BD14 provide additional protection should both the relief system and the EGSE fail.

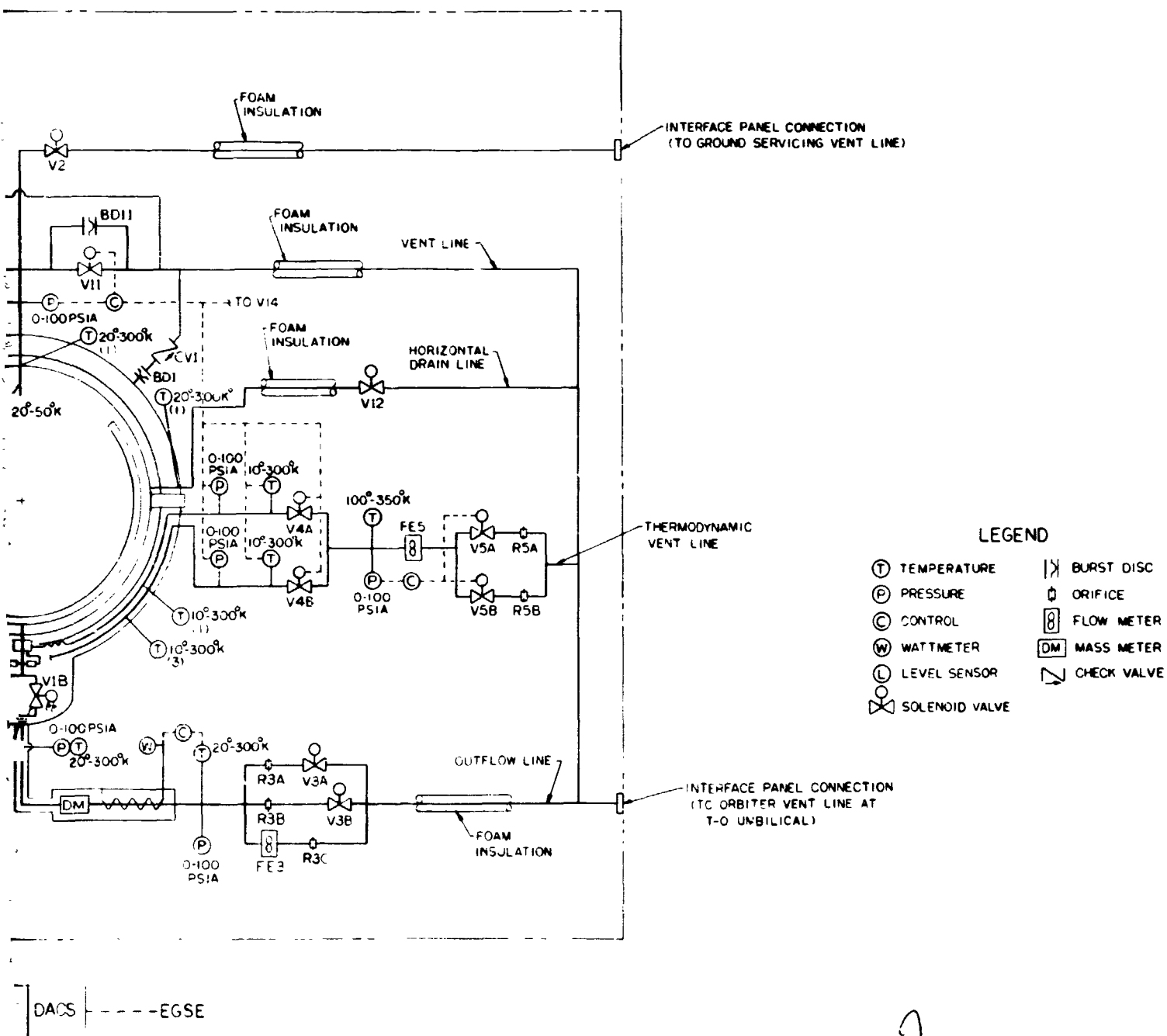
d. LH2 Fill and Drain Check. This test demonstrates the LH2 loading and draining of the CFME-TA, as well as normal gravity chilldown. Timelines to accomplish these tasks will also be verified. Instrumentation will be checked at LH2 temperatures for the first time, along with liquid level sensor accuracy.

Ground support equipment for filling and draining will be configured as shown in Figure IV-4. The CFME-TA, as well as the GSE fill and vent system, will be inerted by pressurizing and then venting the system for a total of five times. This pulse-purging technique provides for adequate gas volume exchange to ensure a GHe concentration of greater than 99 percent. The LH2 tank will be evacuated to less than  $1 \times 10^{-3}$  torr using the vacuum pump connected to the ground servicing vent line. The vacuum will be broken using GHe and a sample of the purge gas taken to verify moisture content is less than 10 ppm. The same pulse-purge technique will then be performed using gaseous hydrogen.

The liquid hydrogen flow is initiated through the fill and drain interface with valves V10 and V2 open. During this initial chilldown, the TVS valves V4A and V4B will be opened to accomplish TVS chilldown. The rate of transfer from the LH2 dewar to the CFME-TA will be controlled by pressurizing the dewar with GHe to 34 to 138 kN/m<sup>2</sup> (5 to 20 psig) in order to maintain a transfer rate not to exceed 81.6 kg/hr (180 lb/hr) of LH2. During the loading, tank temperature sensors will be monitored for indications of chilldown while activation of the liquid sensors will provide positive indications that filling is complete to the 90-95 percent level. A liquid overflow temperature sensor located on the vent standpipe provides backup fill data to the level sensors. Total time for chilldown and loading is estimated to be 30 minutes. At this point flow will be terminated by closing valve V10, and the tank will be pressurized to 30 psia through the ground servicing vent line with gaseous hydrogen in order to collapse any vapor that may have been trapped in the acquisition device channels during tank loading. It is estimated that only two to five minutes will be required to collapse any bubbles that may have been trapped in the channels. This will be verified during the test by monitoring the quality of the outflow. The time required to establish a stable tank temperature will also be determined.

Tank draining will be initiated by pressurizing the tank through the ground servicing vent line with GHe at 69 to 207 kN/m<sup>2</sup> (10 to 30 psig) and forcing LH2 back out the fill/drain line into the facility LH2 dewar or dewar vent system. When the tank is empty, as indicated by system instrumentation, a warmup purge of the tank and the TVS begins. System inerting is accomplished by pulse-purging the CFME-TA with three GHe pressure/vent cycles to simulate the normal inerting process.





**EXCISE FRAME**

Figure VI-2 CFME-TA Schematic

e. Tank Topping. The objective of this test is to confirm the LH2 tank topping procedure and determine the topping timeline. The capability to rechill the GSE transfer line will also be demonstrated. Chilledown of the facility LH2 fill line is accomplished by draining some of the LH2 in the tank through the fill/drain line. Venting in this manner helps chill down the fill/drain line and minimize hydrogen gas boil-off through the tank. When tank pressure reaches  $103 \text{ kN/m}^2$  (15 psia), LH2 flow from the pressurized facility dewar can be initiated. Flow continues until the 95 percent full level is reached as indicated by the liquid level sensors. At this point flow is terminated and the tank is pressurized to  $207 \text{ kN/m}^2$  (30 psia) through the ground servicing vent line, completing the topping-off procedure.

f. Non-Vented Hold Capability Test. This test determines the time it takes for the loaded CFME LH2 tank to increase in pressure from  $207 \text{ kN/m}^2$  (30 psia) to  $379 \text{ kN/m}^2$  (55 psia) with the TVS inactive. This information defines the maximum time the CFME can remain in a non-vented condition on the launch pad in the event of a contingency operation without exceeding the maximum tank operating pressure and blowing the burst disc. The test will be performed in conjunction with the LH2 fill and drain test, and before the thermodynamic vent system test. The CFME-TA LH2 tank will be loaded to 95 percent full and pressurized to  $207 \text{ kN/m}^2$  (30 psia) using GH2. The tank will sit in the loaded condition with the TVS off, and the time for heat leak to increase tank pressure from  $207 \text{ kN/m}^2$  (30 psia) to  $379 \text{ kN/m}^2$  (55 psia) will be determined. When  $379 \text{ kN/m}^2$  (55 psia) is reached, this test will terminate and the thermodynamic vent system test will begin.

g. Thermodynamic Vent System Operation. This test provides one-g data on the operation and performance of the TVS in conjunction with the proper functioning of the DACS microprocessor. Low-g characterization of the TVS will not be obtained until the Shuttle flight data is reduced. Control of tank storage and regulation of the temperature difference between the poles of the storage vessel is accomplished by operating valves V4A and V4B. Proper sizing of orifices R5A and R5B will be verified. The TVS will be activated when tank pressure reaches  $379 \text{ kN/m}^2$  (55 psia). The capability of the TVS to hold pressure constant over a 12 hour period will be evaluated and TVS performance will be monitored. Outflow with tank pressure blowdown to  $310 \text{ kN/m}^2$  (45 psia) and stabilization at this pressure for 12 hours will then be

accomplished while monitoring TVS performance. The degree to which the TVS can maintain tank pressure within  $\pm 7 \text{ kN/m}^2$  ( $\pm 1 \text{ psia}$ ) in the one-g environment will be determined from this test.

h. Vented Ground Hold Capability Test. This test determines how long the loaded hydrogen tank with the TVS operating can remain more than 90 percent full. The amount of hold time before LH2 tank topping-off is required will result from this test. The test will be performed on a loaded (95 percent full) tank which has been pressurized to  $207 \text{ kN/m}^2$  (30 psia) using GHe. Heat exchanger one will be activated from the EGSE and will remain on for the duration of the test. The times at which the 95 percent and 90 percent liquid level sensors drop out will be determined.

i. Horizontal Drain and Tank Inerting. This test demonstrates the capability to drain a loaded tank in the horizontal attitude. The tank will be loaded with LH2 in the horizontal position for the random vibration test. This test will be performed after the random vibration test is complete. Tank draining will be accomplished by forcing liquid out of the horizontal drain line using GHe. Flow in this mode continues until the tank is depleted. The system is inerted by pulse-purging the LH2 tank with GHe.

3. Environmental Tests. The CFME-TA environmental tests include sine vibration and random vibration, which are described in the following paragraphs.

a. Sine Vibration. The objective of this test is to determine the resonant frequencies of the CFME-TA and verify that the unit will survive the sinusoidal vibration environment. The CFME-TA pallet will be subjected to sinusoidal sweep along each of the 3 orthogonal axes over the frequency range from 5 to 35 Hz. The environment is as follows:

Level	$\pm 0.375 \text{ g}$ (zero to peak)
Sweep Rate	1 octave/minute (1 sweep up and down)



The tank must be loaded with LH2 in the horizontal attitude in order to avoid hazardous rotation of a full tank. This special test fill orientation involves loading LH2 through the fill/drain line and venting out of the horizontal vent. Due to the rotation of the tank the liquid sensors are now positioned at the 80 percent (for the 95 percent vertical level) and 85 percent (for the 90 percent vertical level) liquid levels. The tank will be filled to the 85 percent level and then filling will be continued for a calculated time (based on fill rate) to achieve a 90-95 percent fill. The tank will be allowed to self-pressurize to  $138 \text{ kN/m}^2$  (20 psia), at which point periodic gaseous hydrogen venting of the TVS will be initiated to maintain pressure at  $138 \pm 7 \text{ kN/m}^2$  ( $20 \pm 1$  psia). Control of the DACS (which controls the TVS valves), and monitoring of the tank pressure, is accomplished through the EGSE.

The CFME-TA will be attached to the vibration fixture at six points corresponding to the "hard point" mounting locations on the Spacelab pallet. Sketches of the vertical and lateral axes test configurations were shown in Figures III-24 and III-25.

b. Random Vibration. This test verifies that the CFME-TA will survive the random vibration environment for a seven mission life. The vibration tests will be conducted in accordance with the requirements specified in SP-T-0023B (Ref. 16), except as noted herein. The CFME-TA will be subjected to random vibration in each of 3 orthogonal axes as follows:

Composite:	8.72 g rms
20 Hz	$0.00024 \text{ g}^2/\text{Hz}$
20-150 Hz	+ 9 dB/octave
150-600 Hz	$0.10 \text{ g}^2/\text{Hz}$
600-2000 Hz	- 9 dB/octave
2000 Hz	$0.0027 \text{ g}^2/\text{Hz}$
Test Duration:	190 seconds each axis.

Prior to the full level test, a precursor test (30 seconds duration) will be run 6 dB down from the full level to evaluate the control average compared to individual control locations, test article response compared to load limit

abort levels, and fixture response and cross-talk. Because of the size and weight of the test configuration, it is anticipated that control and cross-talk cannot be maintained within the specified tolerances of  $\pm 3$  dB in the 300 to 2000 Hz region. The data from this test will be analyzed and notching of the input spectrum implemented, if required. There shall be no visual evidence of structural damage, performance degradation or permanent set.

### C. CFME Tests.

A summary of the CFME flight article ground tests is presented in the following paragraphs. A more detailed discussion of each is contained in the Ground Test Plan (Ref. 17).

1. In-line Tests. All in-line tests previously identified to be performed on the CFME-TA will also be performed on the CFME, with the exception of the LAD static test and the LAD modal survey, which are performed only on the CFME-TA.

2. Functional Tests. The following functional tests already discussed as part of the CFME-TA testing will be performed on the CFME.

- o Internal and External Leakage.
- o Relief System Verification.
- o LH2 Fill and Drain.
- o LH2 Tank Topping.
- o Non-Vented Hold Capability.
- o Thermodynamic Vent System Operation.
- o Vented Ground Hold Capability
- o Horizontal Drain and Tank Inerting.

In addition, the following functional tests will be performed on the CFME.

a. Liquid Outflow. The objective of this test is to perform both saturated and subcooled liquid outflows, and demonstrate that design flowrates can be provided through the various orifices in the tank outflow line. Limited capability of the liquid acquisition device will also be verified. The functioning of the liquid vaporizer (heaters and associated instrumentation) on low flowrates through orifice R3C will be checked.

This test will be performed after the Vented Ground Hold Capability test is complete and the liquid quantity in the tank has been reduced to 90 percent. The first outflow will be with saturated liquid at a tank pressure of approximately  $175 \text{ kN/m}^2$  (25 psia). Flow will be through orifice R3C, then through R3C and R3B simultaneously, and finally through R3C and R3A simultaneously. Tank pressure is then increased to  $379 \text{ kN/m}^2$  (55 psia). The second outflow will be with subcooled liquid through the same orifice flow paths as in the first outflow. In both cases when outflow is through orifice R3C only, the liquid vaporizer will be activated for a period of time in order to obtain flowrate data from flowmeter FE3.

The flowrate ranges for the three outflow orifices are:

Orifice R3A - 77.1 to 86.2 kg/hr (170 to 190 lbm/hr)

Orifice R3B - 24.9 to 27.2 kg/hr (55 to 60 lbm/hr)

Orifice R3C - 1.36 to 1.81 kg/hr (3.0 to 4.0 lbm/hr)

b. Normal Gravity Abort Drain and Tank Inerting. This test verifies the capability to perform an abort drain and inerting of the tank. The DACS software which performs this abort function will be verified. An abort is considered to be a situation requiring immediate draining (and inerting if time permits) of the LH2 tank without GSE involvement (except for the T-0 vent line interface when on the ground). This test will be accomplished with a loaded hydrogen tank and fully charged GHe pressurant spheres, positioned in the vertical (launch) attitude. The tank will be pressure stabilized with the TVS activated. Tank draining will be performed by forcing liquid out of the tank outflow line using GHe from the pressurant spheres. Maximum flowrate will be obtained by opening valve V3A in the tank outflow line. After the hydrogen tank is depleted, inerting will be initiated from the DACS.

3. High and Low Voltage (Off-Design Performance) Test. The objective of this test is to demonstrate the capability of the CFME electronics to perform at reduced (24VDC) and high (32VDC) voltages. A normal functional test consisting of a tank fill, TVS operation and liquid outflow will be performed with power supply voltage at both 24VDC and 32VDC. All valves shall cycle properly, shall show no signs of overheating or have visual signs of performance degradation. All sensors shall demonstrate acceptable indications at both voltage extremes.

4. Environmental Tests. A CFME environmental tests include random vibration, thermal vacuum and electromagnetic compatibility, as described in the following paragraphs.

a. Random Vibration. The objective of this test is to ensure that the CFME flight article has been designed and fabricated to successfully survive the expected random vibration flight environment. The vibration tests will be conducted in accordance with the requirements specified in SP-T-0023B (Ref. 16), except as noted herein. The CFME flight pallet will be subjected to random vibration in each of 3 orthogonal axes as follows:

Composite:	6.71 g rms
20 Hz	0.00014 g <sup>2</sup> /Hz
20-150 Hz	+ 9 dB/octave
150-600 Hz	0.059 g <sup>2</sup> /Hz
600-2000 Hz	- 9 dB/octave
2000 Hz	0.0016 g <sup>2</sup> /Hz

Test Duration: 60 seconds each axis.

Prior to the full level test, a precursor test (20 seconds duration) will be run 6 dB down from the full level to evaluate the control average compared to individual control locations, test article response compared to load limit abort levels, and fixture response and cross-talk. Because of the size and weight of the test configuration, it is anticipated that control and cross-talk cannot be maintained within the tolerances specified in paragraph 5.2.3 of SP-T-0023B. The data from this test run will be analyzed and notching of the input spectrums implemented, if required, in accordance with SP-T-0023B, paragraph 3.4.1.3, Allowable Level Deviation.

For this test, the CFME must be loaded in the horizontal attitude in order to avoid hazardous rotation of a full tank. This special test fill orientation involves loading LH2 through the fill/drain line and venting from the horizontal vent. Due to the rotation of the tank, the liquid sensors are now positioned at the 80 percent (for the 95 percent vertical level) and 85

percent (for the 90 percent vertical level) liquid levels. The tank will be filled to the 95 percent level and then the liquid fill will continue for a calculated time (based on fill rate) to achieve a 90-95 percent full condition. The tank will be allowed to self-pressurize to  $138 \text{ kN/m}^2$  (20 psia), at which point the TVS will initiate gaseous hydrogen venting to maintain pressure at  $138 \pm 7 \text{ kN/m}^2$  ( $20 \pm 1$  psia). Control of the DACS (which controls the TVS valves), and monitoring of the tank pressure, is accomplished through the EGSE.

b. Thermal Vacuum. The objective of the thermal vacuum tests is to verify the operation of the CFME thermal control system while subjected to the vacuum and temperature extremes which the experiment will see in flight, and to ensure the proper operation of all experiment subsystems over these ranges. The thermal vacuum tests will be conducted in a 10-foot diameter vacuum chamber equipped with radiant heaters and a LN2 cold wall for achieving the required temperatures. The CFME will be positioned in the chamber in the launch attitude. Support of the CFME will be provided through the Spacelab pallet hard point mounting locations. In this manner, the thermal conduction and thermal radiation paths will be simulated. The vacuum chamber pressure will be reduced to less than  $1 \times 10^{-5}$  torr. The hydrogen tank pressure will be maintained at  $138$  to  $310 \text{ kN/m}^2$  (20 to 45 psia) throughout the thermal vacuum tests by the TVS.

Three tests will be conducted with the CFME loaded with LH2 while it is within the chamber:

High-temperature Soak. The CFME will be activated and the vacuum jacket temperature will be stabilized. Stabilization will be achieved when the temperature of the CFME vacuum jacket does not vary more than  $2^{\circ}\text{C}$  ( $3.6^{\circ}\text{F}$ ) per hour. The CFME vacuum jacket will be maintained at this temperature for two hours minimum in order to satisfy the requirements of this test. Vacuum chamber temperature will be maintained at  $130^{\circ}\text{C}$  ( $266^{\circ}\text{F}$ ) throughout the test. TVS performance will be established and flowrates, and inlet and outlet temperatures, will be monitored.

Low-Temperature Soak. The vacuum chamber temperature will be adjusted to maintain  $-160^{\circ}\text{C}$  ( $-256^{\circ}\text{F}$ ) for the duration of the test. Chamber pressure will be reduced to less than  $1 \times 10^{-5}$  torr. The tank assembly vacuum jacket will be maintained at a temperature that does not vary more than  $2^{\circ}\text{C}$  ( $3.6^{\circ}\text{F}$ ) per hour for two hours minimum in order to meet the test requirements. TVS performance will be established, and operation of the LH2 outflow valve and associated instrumentation will be demonstrated by conducting a helium-pressurized LH2 outflow.

Cyclic Temperature Test. The vacuum chamber pressure will be reduced to less than  $1 \times 10^{-5}$  torr. The CFME will be activated and the vacuum jacket temperature will be cycled for a total of 15 cycles between the high and low limits of  $120$  to  $-160^{\circ}\text{C}$  ( $248^{\circ}\text{F}$  to  $-238^{\circ}\text{F}$ ). TVS performance will be evaluated during each cycle. The rate of change of chamber temperature from the cold to the hot condition will follow an exponential curve such that 95 percent of the change occurs in approximately 23 minutes. The remaining 5 percent of the change is linear, reaching maximum temperature in 30 minutes. The rate of change of chamber temperature from the hot to the cold condition will be established such that 95 percent of the change occurs in approximately 68 minutes following an exponential curve. The remaining 5 percent of the change is linear, reaching maximum temperature in 90 minutes. The maximum time that the extreme hot or extreme cold condition will exist is two hours. The environmental temperature will then cycle toward the other condition. This gives the following maximum cycle time:

Cold to Hot	0.5 hours
Hot Condition	2.0 hours
Hot to Cold	1.5 hours
Cold Condition	<u>2.0 hours</u>

Total Maximum Cycle Time	6.0 hours
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This test demonstrates the capability of the CFME to withstand the expected temperature environment fluctuations without any system degradation.

c. Electromagnetic Compatibility Test. This test demonstrates compliance of the CFME with the electromagnetic compatibility (EMC) requirements of NASA specification SL-E-0002, Revision A (Ref. 18). This will assure electromagnetic compatibility with all Space Transportation System equipment. The EMC of the CFME will be demonstrated during the following selected system functional tests using the flight CFME:

RS03	Radiated Susceptibility, E-Field	14 kHz to 10 GHz
RS02	Magnetic Induction Field Susceptibility	
RE02	Radiated Emissions (NB and repetitive BB)	14 kHz to 10 GHz
CS06	Power Line Spike Susceptibility ( $\pm$ 56V)	
CS01	Power Line Conducted Susceptibility	30 Hz to 50 kHz
CS02	Power Line Conducted Susceptibility	50 kHz to 400 MHz
CE01	Power Line Conducted Emissions (NB)	30 Hz to 20 kHz
CE03	Power Line Conducted Emissions (NB)	20 kHz to 50 MHz
TT01	Time Domain Transient and Ripple	

A system functional test will be performed while first subjecting the CFME to the required susceptibility test signals, and then measuring the interference generated by CFME. EGSE will monitor the CFME functions during these tests. During the broadband emissions tests, RE02 and TT01, selected valves will be actuated by EGSE command.

The tests will be done in an RF-shielded room where the CFME is bonded to an RF ground plate. Input power is provided from a 28VDC power source (specified in SL-E-0002 A) having an electrical impedance which simulates the Orbiter power bus. The CFME EGSE will be located in a separate screen room adjacent to the shielded test chamber, and GSE cables entering the test chamber will have overall outer shields which are RF-terminated at both ends. The CFME will be in a functional operating flight hardware configuration with installed EMC monitors, EGSE, and required test tools.

## VII. CFME PLANNING AND COST ESTIMATE

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This section presents a schedule plan and cost estimate for restarting and continuation of the CFME program through delivery of the flight article to the Kennedy Space Center. The program consists of the CFME-TA, the CFME flight article and associated GSE, as described in this report. The specific hardware components and test plans are also as defined in this report. The cost estimate is a budgetary cost (exclusive of fees) and includes burdened labor, computer, travel and material dollars in 1981 dollars. Material costs are rough-order-of-magnitude (ROM) values compiled from written and verbal vendor inputs to specifications and statements-of-work (SOW). Both the schedule plan and the program cost estimate are discussed in greater detail in the paragraphs below.

### A. CFME Program Master Schedule

A program master schedule separated into fifteen tasks, is presented in Figure VII-1. The program start date of July 1, 1983 and flight hardware ship date of October 31, 1986 were specified by the NASA-LeRC Project Manager. The program was structured to meet these milestones while properly accounting for long-lead procurement and sequential build of the CFME flight hardware following completion of CFME-TA testing. The latter sequential is important to preclude premature commitment to relatively expensive fabrication and assembly of the flight article until adequate structural design verification is obtained during CFME-TA vibration testing.

The major program milestones are a kick-off meeting and submittal of a project work plan within one month of contract go-ahead. An incremental Critical Design Review (ICDR) is scheduled for 6 months after go-ahead to review experiment definition and detailed design changes resulting from CFME integration with the rest of the Cryogenic Fluid Management Facility (CFMF), of which the CFME is to be the supply tank for up to seven flight tests. The Phase II flight and ground safety reviews are planned for two months after the ICDR. The flight review will be held at NASA-JSC and the ground review will be held at NASA-KSC. The Final Design Review (FDR) is scheduled following the

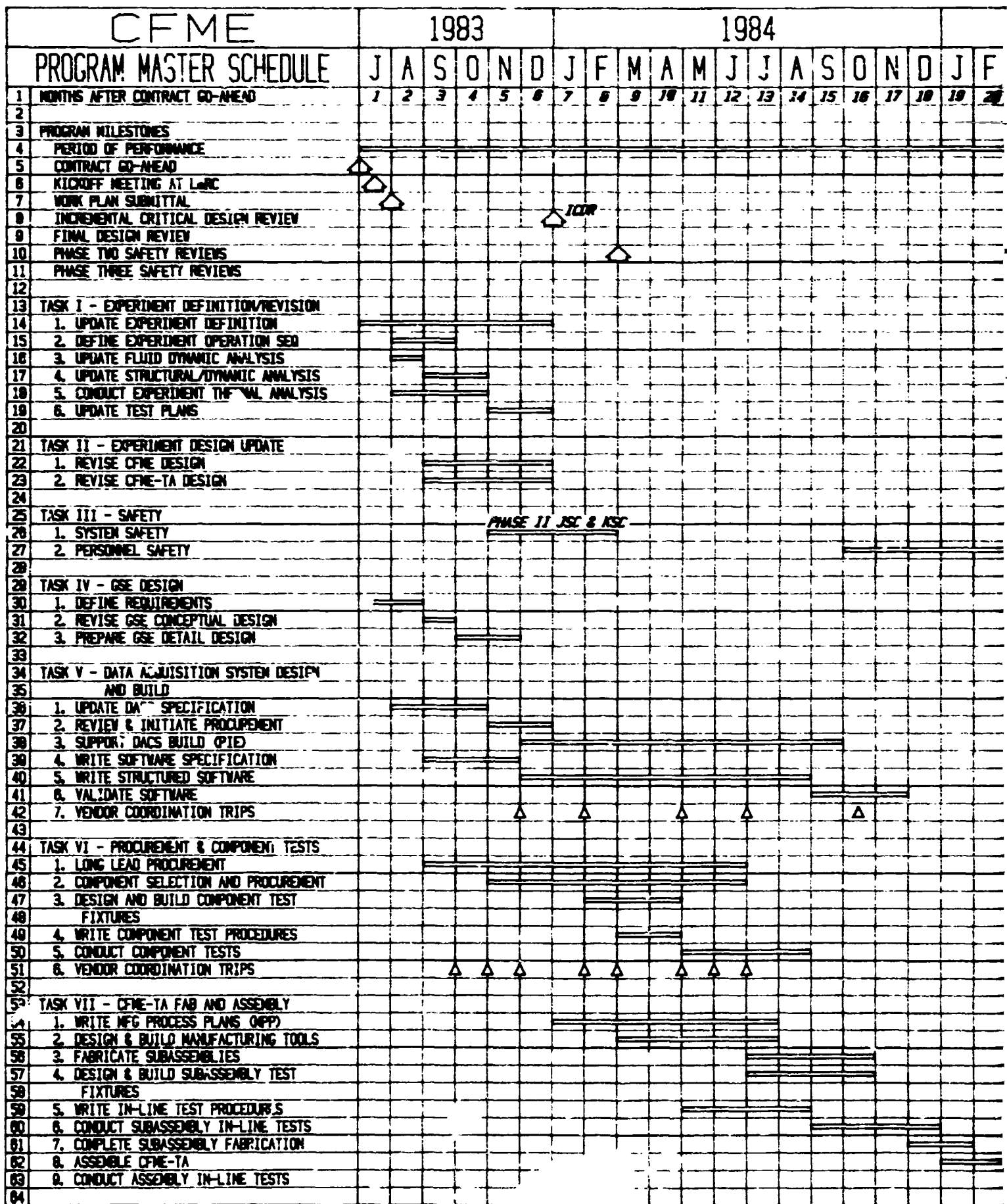


CFME-TA testing and prior to commitment for final assembly of the CFME flight article. The Phase III flight and ground safety reviews are planned for mid-October 1986, followed by the preship review, and pack and ship of the flight article and associated GSE to the KSC.

It is anticipated that the detailed design of the CFME will introduce some changes for the CFME, particularly in the valve assembly panel and DACS interfaces, due to integration of a receiver tank and associated instrumentation with the CFME supply tank. The Task I - Experiment Definition effort will address these changes, and the Task II - Detail Design Update will identify and incorporate changes to the already completed detailed drawings. Task IV will involve a similar design function for the deliverable GSE. (It should be noted that this task does not include ground test fixtures and GSE as it did for the CFME program reported herein; these are included in the plan and cost estimate under the applicable specific test tasks). Task III includes both system safety for preparation and presentation of the Phase II and Phase III flight and ground safety reviews, and personnel safety during the CFME-TA and CFME ground test activities.

The Data Acquisition and Control System (DACs) design and build has been broken out as a separate task, Task V, because of the magnitude and diversity of the effort involved. The update of the hardware specification and generation of the detailed software specification will be accomplished under this task, and the results presented in detail at the ICDR. Close coordination with the DACS vendor will be required to assure compatibility between the hardware capabilities and the software requirements. This Task V activity must start within a month following contract go-ahead due to the flight hardware and EGSE build and acceptance lead time required to support assembly and test of the CFME-TA. Procurement must be initiated prior to the ICDR to support the schedule, although final details can be firmed-up immediately following the ICDR as long as they do not affect the basic computer and power distribution units, and the interfaces between these elements and the EGSE.

All hardware procurement is accomplished under Task VI. Component selection and long lead parts procurement will have to start prior to ICDR, since some elements such as the tank shells and electrical connectors require



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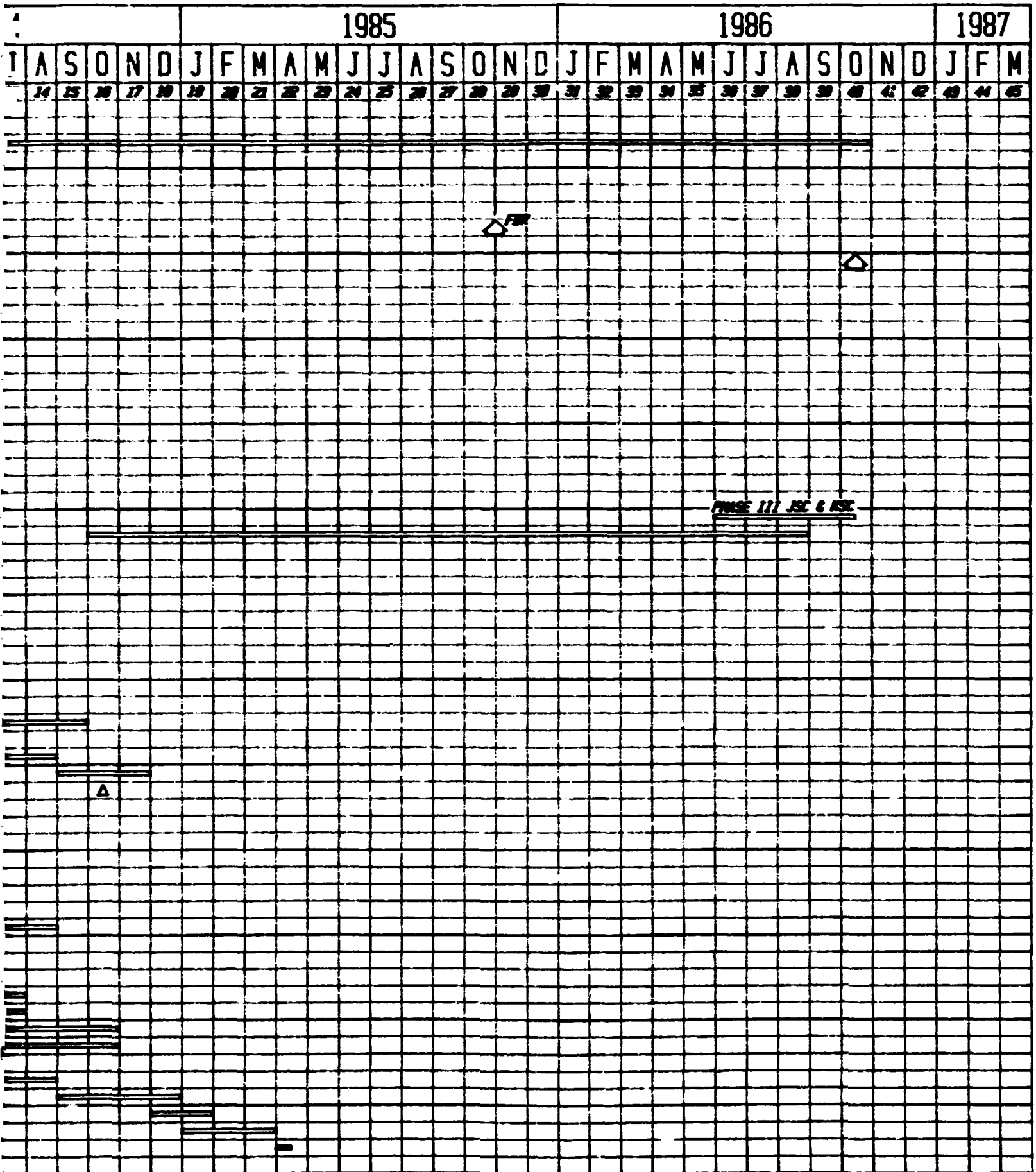
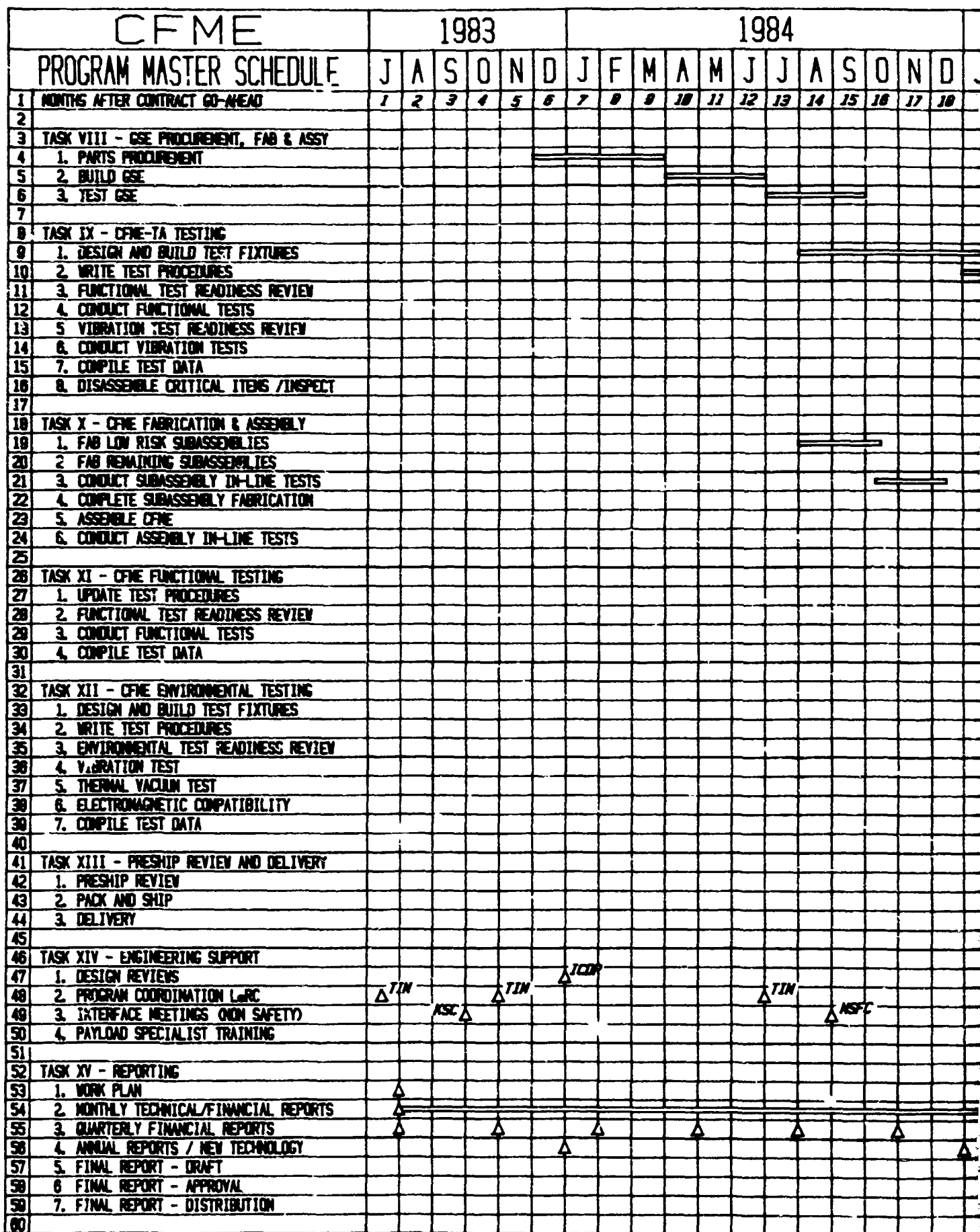


Figure VII-1 CFME Program Master Schedule MARTIN MARIETTA

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nine month lead times. The Task VII-CFME-TA Fabrication and Assembly begins immediately following the ICDR, with actual build of the subassemblies starting twelve months after contract start. The CFME-TA will be completed by the 22nd month. The Task VIII-GSE Procurement, Fabrication and Assembly will run concurrent with the Task VII-CFME-TA build to provide the GSE support items for experiment handling and servicing.

Test fixtures for functional and vibration testing will be designed and built early during the Task IX-CFME-TA Testing effort. These same fixtures will be used again during the CFME Functional and Environmental Testing, Tasks XI and XII respectively. The critical parts of the CFME-TA will be disassembled and inspected prior to commitment to final assembly of the CFME flight hardware, Task X. One build of all detailed parts for both the CFME-TA and the CFME is planned. The low risk subassemblies of the CFME will be fabricated and tested concurrently with those similar subassemblies of the CFME-TA. The remaining subassemblies of the CFME will not be fabricated until post-test inspection of the CFME-TA has been completed.

The thermal vacuum test fixtures are the only new fixtures not previously built for the CFME-TA tests that are required for the Task XII-CFME Environmental tests, and these fixtures will be designed and built early enough to permit facility readiness for timely support of the test schedule. Following completion of the thermal vacuum and electromagnetic compatibility tests, the Phase III safety packages will be finalized and the appropriate safety reviews held at NASA-JSC and NASA-KSC. Once the appropriate safety certifications are prepared, the CFME flight package and associated GSE are ready for the preship review and packaging for delivery to the KSC.

Tasks XIV and XV involve the engineering support and reporting activities for the program. Payload Specialist training during the CFME functional tests is included in the Task XIV - Engineering Support effort.

#### B. CFME Program Cost Estimate

A budgetary cost estimate (excluding fees) was prepared around the program plan just discussed, and the results are summarized in Table VII-1. Numbers in the table are thousands of dollars (1981 dollars). The costs are grouped

into six categories and spread by calendar year. The tasks that make up the program plan have been combined to make up the six cost categories, and the breakdown is as follows:

**Category A. CFME Definition and Design Update**

Tasks I, II and the system safety part of III

**Category B. CFME-TA Procurement, Fabrication and Test**

Tasks VI (but only including \$814,300 of material), VII  
IX and personnel safety part of III.

**Category C. GSE Design, Fabrication and Assembly**

Tasks IV and VIII

**Category D. CFME Fabrication and Assembly**

Tasks VI (including \$1,218,700 of material), V and X

**Category E. CFME Test**

Tasks XI, XII and personnel safety part of III.

**Category F. Engineering Support and Other Technical Services**

Tasks XIII, XIV and XV

The portion of the costs attributed to material costs are also summarized under the appropriate categories. It should be noted that the last six months of calendar 1983 are split between fiscal 1983 and fiscal 1984; the large material dollar expenditure (\$2.0 million), which makes up nearly 80 percent of the costs for this time period, can be spread over two years' funding allocation. The large expenditure for material (components, DACS, instrumentation, etc) reflects significant inflation increases over the past several years.

*Table VII-1 Time-phased Budgetary Cost Estimates (Excluding  
Fee) in 1981 Dollars  
(Numbers are thousands of dollars)*

	Calendar 1983	Calendar 1984	Calendar 1985	Calendar 1986	Total
A. CFME Definition and Design Update	\$170.1	\$8.8		\$28.0	\$206.9
B. CFME-TA Proc, Fab and Test	1070.5 (814.3 Mt1)	404.5 (67.8 Mt1)	267.8		1742.8 (882.1 Mt1)
C. GSE Design Fab and Assy	21.6	55.2 (20.0 Mt1)			76.8 (20.0 Mt1)
D. CFME Fab and Assy	1263.0 (1218.7 Mt1)	210.2	96.7	149.8	1719.7 (1218.7 Mt1)
E. CFME Test			38.6 (24.4 Mt1)	283.6	322.2 (24.4 Mt1)
F. Eng Support and Other Tech Services	32.6	50.0	38.3	54.4	175.3
	\$2557.8 (\$2033.0 Mt1)	\$728.7 (\$87.8 Mt1)	\$441.4 (\$24.4 Mt1)	\$515.8	\$4243.7 (\$2145.2 Mt1)



## VIII. CONCLUSIONS AND RECOMMENDATIONS

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### A. Conclusions.

The Cryogenic Fluid Management Experiment (CFME) will provide the first engineering data on low-g storage and outflow of liquid hydrogen. The design meets the seven-mission requirement and can easily be integrated as a Shuttle payload or as a subassembly of the Cryogenic Fluid Management Facility (CFMF).

The experiment was designed to demonstrate the feasibility of combining a fine-mesh screen fluid acquisition system with a thermal control system to provide on-demand vapor-free liquid cryogenics in space. Instrumentation was specifically included to provide a performance evaluation of the pressurization system, thermodynamic vent system, vapor-cooled shield, trunnion mount, multilayer insulation, liquid acquisition device and outflow system. Data acquired will be significant in establishing design criteria that can be applied to the design of subcritical tankage up to 4.57 m (15 ft) in diameter.

The CFME was designed to "Fail Safe" in an autonomous operating mode without any Payload Specialist involvement or commands from the EGSE when on the ground. No single-point failures exist which could cause an unacceptable hazardous condition while the CFME is either on the launch pad or during operation on-orbit. All Phase I Safety hazards are controllable, with no hazard potential greater than that which exists when servicing or expelling the Orbiter Power Reactant Storage Tanks.

The ground support equipment required to service the CFME helium spheres and liquid hydrogen storage and supply tank exist at KSC, and may be used without extensive modification.

### B. Recommendations.

During the design effort, several areas of concern developed due to the lack of adequate design and performance data. It is desirable to verify the design approach and analysis prior to commitment to fabrication and test verification of the entire assembly. Implementation of the following

recommendations will minimize cost and schedule risk once the fabrication, assembly and testing of the CFME is initiated.

1. The liquid hydrogen tank support trunnion designs are based on limited fatigue data for S-glass/epoxy composites. We recommend that a program be established to determine the structural integrity of the trunnions using the techniques proposed in the Trunnion Test Plan (Ref. 14).
2. There is a lack of suitable liquid hydrogen mass flow instrumentation to accurately measure experiment flowrates. Due to the importance of the accuracy of these data with respect to the successful evaluation of the CFME performance, it is highly desirable to conduct a program to prove the capability of a selected flowmeter to operate with liquid hydrogen. The capability to detect two-phase flow in the outflow line is a desirable feature of the flow instrumentation, and verification (and calibration) of a device for this function should be pursued as early as possible to allow time for modifications and design verification.
3. Throughout the design effort we found a notable reluctance on the part of some component suppliers to firmly commit to supplying suitable flight-proven or flight-type items for liquid hydrogen use. This situation could have a potential impact on the program when funding for procurement, fabrication and assembly is available. In many cases, the limited number of vendor sources for some components imposes program risks which are difficult, and in some cases impossible, to eliminate by competitive selection. It is recommended that an interim appraisal of component availability be made far enough ahead of funding availability and program go-ahead to preclude major program impacts.
4. Since there are no overriding technical issues still to be resolved before a commitment can be made to fabrication, assembly and ground test verification, we recommend that the CFME-TA build and test effort be initiated as soon as possible. This will allow timely certification of the design to permit a high degree of flexibility

for scheduling the flight test of the CFMF. This will also allow any design modifications resulting from the CFME-TA tests to be incorporated in the flight hardware without reworking hardware already assembled because of schedule constraints.

# APPENDIX A ABBREVIATIONS AND ACRONYMS

BTU	British Thermal Unit
C	Centigrade
CDR	Critical Design Review
CEC	Consolidated Electrodynamics Corporation
CFME	Cryogenic Fluid Management Experiment
CFME- TA	Cryogenic Fluid Management Experiment - Test Article
cm	Centimeter
CPU	Central Processing Unit
CSAM	Cryogenic Storage Analysis Model
DACS	Data Acquisition and Control System
DC	Direct Current
db	decibel
EGSE	Electrical Ground Support Equipment
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
F	Fahrenheit
ft	foot
g	force of gravity
GHe	gaseous helium
GHz	giga Hertz
GH2	gaseous hydrogen
GSE	Ground Support Equipment
Hr	hour
HX	Heat exchanger
Hz	Hertz
I/O	Input/Output
K	Kelvin
kg	kilometer
kHz	kilo Hertz
km	kilogram
kN	kilo Newton
KSC	Kennedy Space Center
LAD	Liquid Acquisition Device
lb	pound
lbm	pound mass
LeRc	Lewis Research Center
LH2	liquid hydrogen
LN2	liquid nitrogen
m	meter
MHz	mega-Hertz
min	minute
MLI	Multilayer Insulation
N	Newton
nmi	nautical mile
OCP	Operation Control Panel
OMS	Orbital Maneuvering System
PDU	Power Distribution Unit
PDR	Preliminary Design Review
PPM	parts per million
PROM	Programmable Read-Only Memory

ABBREVIATIONS  
AND  
ACRONYMS (cont'd)

PRSA	Power Reactant Storage Assembly
PRSD	Power Reactant Storage and Distribution
psi	pound per square inch
psia	pound per square inch absolute
psig	pound per square inch gage
RAM	Random Access Memory
RCS	Reaction Control System
RMS	root mean square
scc	standard cubic centimeter
SCI	SCI Systems, Inc., Huntsville, Alabama
sec	second
SOW	Statement of Work
SSB	Space Support Building
TBD	to be determined
TVS	Thermodynamic Vent System
VAB	Vehicle Assembly Building
VCS	Vapor Cooled Shield
VDC	volts direct current
VJ	Vacuum Jacket
W	Watt

APPENDIX B  
Cryogenic Fluid Management Experiment  
Drawing Tree  
(849 CFME XXXX)

1000		Cryogenic Fluid Management Experiment
1048A		Tank Assembly
1012		Hemisphere, Vacuum Jacket
1014		Girth Ring, Vacuum Jacket
1018		Tube, Bimetallic
1019		Tube Clip
1029		Bracket Assembly
1030		Support Flange
1032		Support Assembly
1033		Reinforcement Ring, Vacuum Jacket
1034		Valve Housing, Vacuum Jacket
1035		Fixed Trunnion
1036		Floating Trunnion
1037		Vapor-Cooled Shield Assembly
	1013A	Hemisphere, Vapor-Cooled Shield
	1019	Tube Clip
1038		Pressure Vessel Assembly
	1011	Hemisphere, Pressure Vessel
	1015	Liquid Acquisition Assembly
	1016	Channel
	1017	Tube, Bimetallic
	1020A	Truss
	1021A	Strut
	1022	Lower Manifold
	1023	Manifold Assembly
	1024	Torque Channel
	1026	Screen Assembly
	1025	Perforated Plate
	1027A	Angle
	1018	Tube, Bimetallic
	1028	Girth Ring, Pressure Vessel
	1031	Clip Assembly
	1041	Fitting, Fill and Drain
	1042	Fitting, Vent
	1043	Elbow
	1044	Reducer, Outlet
	1045	Manifold, Tank Outlet
	1084	Temperature Sensor Installation
1039A		Viscojet Housing
1040		Reducer, Viscojet Housing
1046		Sleeve, Horizontal Drain
1047		Cover, Outlet Manifold
1049		Tubing Clamp
1050		Vent Tube, Vertical
1051		Fill and Drain Tube
1052		Horizontal Drain Tube
1053		Outflow Tube
1054		Jacket, Bimetallic Tube
1055		Jacket, Bimetallic Tube

Cryogenic Fluid Management Experiment  
Drawing Tree  
(continued)

1056	Reducer, Fitting
1057	Adapter, Vacuum Jacket
1058	Sleeve, Vacuum Jacket
1059	Spacer, Vacuum Jacket
1060	Trunnion Housing
1061	Flange, Trunnion Housing
1062	Cap, Fixed Trunnion
1063	Disc, Floating Trunnion
1064	Ring, Back up
1065	Tube Clip
1066	Clip, Tube Support
1067	Bracket, Valve Support
1068	Torsion Member
1069	Guide Pin
1070	Coupling, 3/16 Tube
1071	Bracket, VCS Support
1072	Adapter
1073	Strap, Restrainer
1074	Housing, Instrumentation Connector
1075	Bimetallic Tube
1076	Vent Tube, Horizontal
1077	Clamp Assembly
1084	Temperature Sensor Installation
1111	Bracket, Tank Support
1112	Stud, Tank Support
1079A	Helium Sphere Support Assembly
1081	Strut, Tank Support
1082	Clevis, Tank Bipod Support
1083	CFME Mounting Pallet
1079A	Helium Sphere Support Assembly
1082	Clevis, Tank Bipod Support
1089	Bracket, Hard pt. 11
1090	Housing, Hard pt. 12
1091	Fitting Assembly, Hard pt. 7 and 15
1092	Attach Fitting, Hard pt. 8 and 16
1093	Clevis, Hard pt. 7 and 15
1094	Clevis, Hard pt. 8 and 16
1085	Tube, Bimetallic
1086	Tube, Bimetallic
1087	Sleeve, Vacuum Jacket
1088	Adapter, Helium Sphere
1095	Servicing Line Interface Panel
1059	Spacer, Vacuum Jacket
1096 *	Cabinet Assembly
1097 *	Jacket, Flowmeter Housing
1098 *	Cover Plate

Detailed Drawing not included as part of design effort

**Cryogenic Fluid Management Experiment  
Drawing Tree  
(continued)**

1099	•	Cover Plate
1100	•	Housing, Fill Valve
1101	•	Cover Plate, Fill Valve Housing, Top
1102	•	Cover Plate, Fill Valve Housing, Bot.
1103	•	Insulator, Outflow Valve
1104	•	Collar, Vacuum Jacket
1105	•	Sleeve, Reducing
1106	*	Reducer, 5/8" x 3/8"
1107	•	Reducer, 3/8" x 1/4"
1108	•	Clamp Block, Pressure Transducer
1109	*	Orifice
1110	•	Reducer 3/4" x 1/4"
1113		Junction Box, Electrical Interface
1114	*	Insulation Fabrication and Installation
1115		Schematic
1500		Electrical System Wiring Diagram
1501		Tank Assembly - Wiring Diagram
1502		Valve Panel Assembly - Wiring Diagram
1600		Data Acquisition and Control System

\* Detailed Drawing not included as part of design effort.



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